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WCCM AUTOMATED COMMAND AND CONTROL SUPPORT

Pattern Analysis and Recognition Corporation

ROME AIR DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
GRIFFISS AIR FORCE BASE, NEW YORK 13441

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This report describes the software programs developed by Pattern Analysis and Recognition Corporation for the control and monitoring of the Wideband Command and Control Modem Automated Test System at Rome Air Development Center. The first section describes the Test System and the objectives of the project. A functional description of the software is given in the second section. The User's Manual for the system is contained in the third section which gives the

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operating instructions and depicts the organization of the programs. The Appendix presents the derivations of the mathematical formulas which are used to locate the RPV.

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EVALUATION

The result of this effort was the development and implementation of software routines for the automated control of an operational system using Wideband Command and Control Modems developed under RADC Contract F30602-72-C-0500. These routines, written for a GT-44 Graphics Display System, will allow operator control of the WCCM Automated Test System in a real time scenario through the use of an interactive graphics display. Test and evaluation of WCCM can now be accomplished through the use of this software and past mission analysis of data acquired from real time flight tests.

Stanley M. Yanik

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Project Engineer

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SECTION 1

INTRODUCTION

This document reports on work performed by Pattern Analysis and Recognition Corporation (PAR) under Contract F30602-76-C-0101 to the Rome Air Development Center (RADC). Under this contract PAR has designed and implemented programs to control and monitor the performance of the Wideband Control and Command Modems (WCCM) Automated Test System at RADC. This facility consists of a GT-44 Graphics Display System and the WCCM Experimental Model. The GT-44 contains the following equipment:

PDP 11/40 Central Processor (KD 11-A) with 16K words of memory (MR 11-U)
Two Disk Drives (RK-05) and Controller (RK-11)
VT-11 Display Processor with 17" Graphics Terminal (GT) and Light Pen
RT-11 Operating System and FORTRAN compiler
Two DECKIT 11-H I/O interfaces to the WCCM hardware

The WCCM Experimental Model, built by Hughes Aircraft, has two remotely-piloted vehicle (RPV) spread spectrum modems and a companion ground control station (GCS) which currently has three timing and control units (TCU) and a load simulator to simulate the operation of a number of RPV's.

The objective of this program has been to provide an automated mode of operation for the WCCM Experimental Model. With the software provided by PAR it is now possible to command and control the modems, to find the position of an RPV by processing the range estimates from the GCS, and to collect data on the operation of spread spectrum modems in various realistic situations.

1.1. SUMMARY OF WCCM CHARACTERISTICS

The WCCM Experimental Model has seven identical pseudo-random noise (PN) generators: 2 in each RPV modem and 1 in each TCU of the GCS. The PN generators output a 2 megachip sequence at a rate of 60 MHz to modulate and demodulate the communications data. These PN generators are manually programmed by switches to any of 63 PN sequences, where the primary programming restraint is that both the transmit and receive end of each data link must have the same PN sequence. In other words, the GCS transmit and both RPV receive PN generators are set to one PN sequence, while the three GCS receive and both RPV transmit PN generators are set to a different PN sequence.

1.1.1. Forward Or Up Link

The RPV command and control data is set into 80 bit words in the GCS and transmitted at the chosen rate to the RPV. The 80 bit word is made up of 10 parity bits, a command/control bit, 6 RPV address bits, and 63 information bits. As many as 25 RPV's may be operated with the GCS. The setting of the Manual Cycle Input Switch specifies the number of RPV's. The Up Link capabilities are summarized in Table 1.

Uplink Data Rates(kbps)	Allowed Manual Cycle Input	Total Messages Per Frame	Messages Per RPV Per Frame	Command Data Rate Per RPV Per Frame (bits)	Processing Gain (dB)
12	1	5	5	315	37
	5		1	63	
15	1	6	6	378	36
	2		3	189	
	3		2	126	
	6		1	63	
20	1	8	8	504	35
	2		4	252	
	4		2	126	
	8		1	63	
24	1	10	10	630	34
	2		5	315	
	5		2	126	
	10		1	63	
30	1	12	12	756	33
	2		6	378	
	3		4	252	
	4		3	189	
	6		2	126	
	12		1	63	
40	1	16	16	1008	32
	2		8	504	
	4		4	252	
	8		2	126	
	16		1	63	
60	1	25	25	1575	30
	5		5	315	
	25		1	63	
120	1	50	50	3150	27
	2		25	1575	
	5		10	630	
	10		5	315	
	25		2	126	

Table 1 Uplink Characteristics

1.1.2. Return Or Down Link

The return link has a spread spectrum signaling rate of 60 MHz in three modes:

1. continuous telemetry (CT)
2. video and telemetry (V&T)
3. time division multiple access (TDMA)

In each mode the telemetry (TM) data is transmitted from the RPV to the GCS at a constant rate of 2400 bps. The 40 bit TM words consist of 7 parity bits, 18 RPV modem status bits, and 15 RPV aircraft status bits. The GCS contains only one receive modem to serve both RPV modems and the load simulator. Thus, if any TCU is set to a continuous mode (CT or V&T), the other TCU's must be set to "OFF".

The TDMA mode allows both RPV's and the load simulator to simultaneously transmit to the GCS. This is achieved by dividing each sub-frame (1/60 second) into 1000 intervals (16.67 microsecond spacing) and using the time assignment function to specify the time of the TM data burst transmission with respect to a frame mark. By basing the time assignments on the range differential between the RPV's, the number of RPV's, and the burst duration, which is data rate dependent, all signals from the RPV's will arrive at the GCS separate in time and with no overlap. Table 2 gives the TDMA burst characteristics.

1.2. WORK SUMMARY

The work done for this project may be divided into two major tasks. The first was to develop routines to read and analyze the modem status data under the appropriate conditions, to transmit command and control data to the modems after the proper constraints had been satisfied, and to give the current state of the system on the GT. The second task was to design position algorithms which would provide a location accuracy of 3m with a minimum of computation.

1.2.1. Operational Software

The software definitions necessary for the proper operation of the WCCM Automated Test System were given in Chapter IV of the final technical report, #RADC-TR-75-0297, by the Hughes Aircraft Company, hereinafter called the Hughes Report. The routines written by PAR followed the general outline of the flow diagrams of this report. The major difference is that all the System-User interaction takes place via the light pen and light buttons displayed on the GT, rather than by typing various codes on the terminal. The applications-independent portions of the display subroutines which were developed by PAR for the Multilateration Radar Surveillance/Strike System were used as a basis for the WCCM display generation. All programs were initially implemented and debugged on an 11/45 computer system which was essentially identical to the GT-44 at RADC. Therefore, in order to simulate the action of the WCCM hardware, a scenario generator was written to provide data files to simulate an RPV flight including the expected states of the modems. Details of the routines are fully described in the succeeding sections.

Data Rate (kbps)	Burst Duration (msec)	% of Subframe	Time Slot Increments
12	3.66	22.0	220
15	2.94	17.6	176
20	2.20	13.2	132
24	1.83	11.0	110
30	1.47	8.8	88
40	1.10	6.6	66
60	0.73	4.4	44
120	0.37	2.2	22

Table 2 TDMA Burst Characteristics

1.2.2. Position Algorithms

This project required the location of an RPV for three different scenarios:

(1) TRILATERATION - range measurements between the RPV and three GCS's

(2) BILATERATION - range measurements between the RPV and two GCS's plus the RPV altitude.

(3) RELATERATION - trilateration for a relay aircraft and bilateration using the RPV, the relay, and one GCS.

The algorithms proposed in the Hughes Report (pp. 180-199) determined the RPV location by means of an iterative approach. PAR performed an evaluation of these algorithms to determine their suitability for this application. The results of this study showed that the Hughes iteration scheme converged poorly, took too much time, and was quite sensitive to round-off errors. Therefore, PAR designed algorithms to calculate the position of an RPV in ONE step. These algorithms also provide significantly better location estimates for the hardware provided. This is done by means of a series of coordinate transformations which are fully described in the Appendix of this report.

SECTION 2

FUNCTIONAL DESCRIPTION

This section describes the various functions performed by the software to operate the WCCM modems and to analyze the data obtained from them. A description of the scenario generator which simulates status and range data is also included. In order to make best use of the 16K words of core available in the GT-44, the programs are divided into two overlays. The first initializes all the parameters and the second performs all the control and analysis operations. In the first overlay all user-system interaction is through the keyboard of the terminal, while in the second overlay the interaction is via the light buttons displayed on the GT.

The display format is shown in Figure 1. The screen is divided up into five areas which are indicated on the perimeter. Area 1 shows the current status of the modems. Area 2 passes information to user about command constraints or error conditions. Area 3 contains all system command light buttons and with one exception is the only light pen sensitive area of the screen. Area 4 graphically displays the GCS, RPV, and relay locations as squares, a circle, and a triangle, respectively. The heading of the RPV is indicated by the "tail" on the circle. The origin of the coordinate system is shown by the intersection of the crosshairs. The SET CENTER command displays a light-pennable cursor which may be moved with the light pen to the point desired as the center of the display. The display is automatically scaled to keep all the displayed symbols within the bounds of the area. The scale in the upper left corner of area 4 indicates the number of kilometers per inch. Area 5 gives numerically the locations of the RPV and the relay aircraft. The unit of length is the kilometer. The scenario is shown in the lower left corner of this area.

2.1. INITIALIZATION AND EXECUTION

The first overlay gets all the parameters and sets all the variables needed to operate the WCCM Automated Test System in the second overlay. The user specifies the type of input as REAL or FAKE depending on whether the data is read from the interface to the WCCM hardware or from a simulated data file on disk. If fake, the name of the desired input file must be typed. The scenario type is input as TRILATERATION (using three GCS's), BILATERATION (using two GCS's and the RPV altitude), RELATERATION (trilateration with a relay aircraft and bilateration using the relay, one GCS, and the RPV altitude), or STATUS ONLY (only status data is analyzed). The maximum number of RPV's which can be entered is 25, but Table 1 should be consulted to ensure that the value input is consistent with the chosen uplink data rate and the setting of the Manual Cycle Input switches. The GCS coordinates in units of kilometers are normally found in a data file on DKØ named COORDS.DAT and are typed out on the terminal. New values may be typed in or old values accepted with a carriage return. In any case the file is rewritten on disk. The units in which the RPV altitude must be entered are feet divided by 1ØØ. This is in

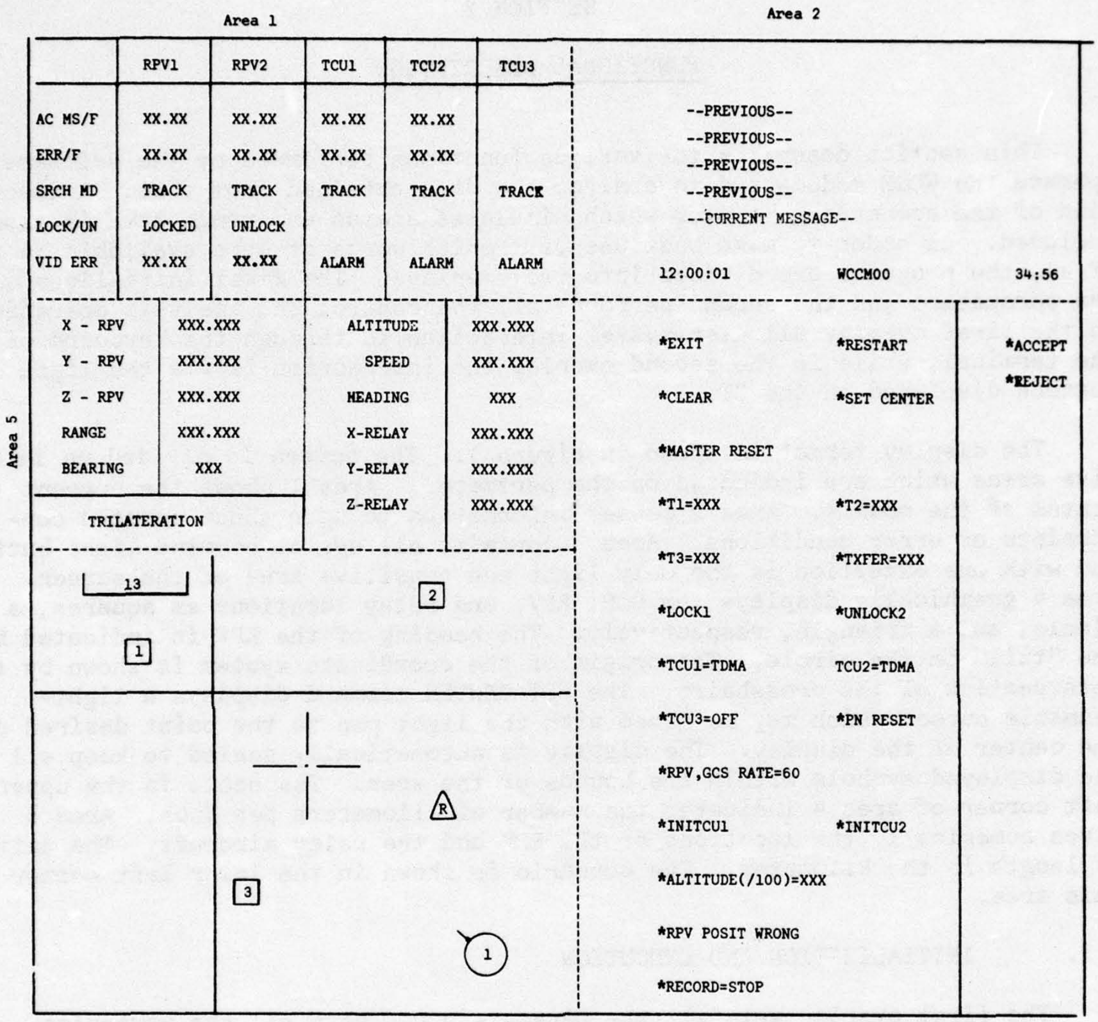


Figure 1 WCCM Display Format

keeping with the expectation that during the flight testing of the WCCM modems the barometric altimeters used will be calibrated in feet and be accurate to only ±50 feet. For all scenarios except STATUS ONLY, a subroutine is called which calculates the direction cosines of the coordinate transformation matrix (see Appendix) and other constants used to facilitate the RPV position computations. The date, if not already in the system word, is input as day-month-year, and the time, as hour:minute:second. The display initialization subroutine then formats the display buffer and sets all the display parameters. The variables which are needed for the second overlay are written from the common area to a file on DKØ named COMMON.DAT.

When the second overlay starts execution, the common data is retrieved from the disk and the display is restarted. If the input is REAL, the WCCM interface addresses are specified. Otherwise, FAKE input is assumed and simulated interface addresses are used for data input. After the operation of the programmable clock is initiated, the executive loop is entered. This loop consists of calls to the command interpretation, command output, data recording, and display update routines. When the restart/exit flag is set by light penning the RESTART or EXIT buttons, the programmable clock is stopped, any open files are closed, and the first overlay is restarted or an exit is made to the RT-11 monitor.

2.2. STATUS

2.2.1. Data Description

The status and range data is read from the eight input addresses of the DECKIT 11-H I/O interfaces; one DECKIT Interface is designated as Unit 1, the other, Unit 2. A brief description of the data categories is given below and summarized in Table 3.

I. Status Data

A. Uplink Configuration

1. <u>Transmit PN Lock/Unlock</u> determines whether the RPV PN generators are locked or unlocked.

   a. RPV 1 - bit 8, word 2, unit 1 set/clear
   b. RPV 2 - bit 8, word 2, unit 2 set/clear
   c. Data invalid if TCU is not tracking RPV

2. <u>Search Mode</u> gives the mode in which an RPV is searching if it is searching

   a. RPV 1 - bits 11-12, word 1, unit 1 = Ø,1,2,3
   b. RPV 2 - bits 11-12, word 1, unit 2 = Ø,1,2,3
   c. Data invalid if TCU is not tracking RPV or RPV is tracking TCU

3. RPV Search/Track Status determines whether the RPV is searching or tracking

   a. RPV 1 - bit 1Ø, word 2, unit 1 set/clear
   b. RPV 2 - bit 1Ø, word 2, unit 2 set/clear
   c. Data invalid if TCU is not tracking RPV

4. RPV Receive Data Rate is used to ensure that the data rate setting of the RPV is correct

   a. RPV 1 - bits 13-15, word 1, unit 1 = Ø-7
   b. RPV 2 - bits 13-15, word 1, unit 2 = Ø-7
   c. Data invalid if TCU is not tracking RPV

B. Downlink Configuration

1. TCU Search/Track Status determines whether the TCU is searching or tracking

   a. TCU 1 - bit 7, word 2, unit 1 set/clear
   b. TCU 2 - bit 7, word 2, unit 2 set/clear
   c. TCU 3 - bit 2, word 2, unit 1 set/clear

2. Alarm indicates whether TDMA contention exists or not

   a. TCU 1 - bit 6, word 2, unit 1 set/clear
   b. TCU 2 - bit 6, word 2, unit 2 set/clear
   c. TCU 3 - bit 3, word 2, unit 1 set/clear

II. Data Quality

A. Uplink Configuration

1. RPV Accepted Messages per frame counts the number of messages accepted by each RPV

   a. RPV 1 - bits 6-1Ø, word 1, unit 1
   b. RPV 2 - bits 6-1Ø, word 1, unit 2
   c. Data invalid if TCU not tracking RPV

2. RPV Accumulated Parity Errors per frame counts the number of messages with parity errors received by each RPV

   a. RPV 1 - bits 1-5, word 1, unit 1
   b. RPV 2 - bits 1-5, word 1, unit 2
   c. Data invalid if TCU not tracking RPV

3. Command Acknowledge is used to determine if a link command has been received and acknowledged by an RPV

   a. RPV 1 - bit 9, word 2, unit 1 (set=ack)
   b. RPV 2 - bit 9, word 2, unit 2 (set=ack)

B. Downlink Configuration

1. TCU Accepted Messages per frame counts the number of messages accepted by a TCU

   a. TCU 1 - bits Ø-1, word 2, unit 1 = Ø,1,2
   b. TCU 2 - bits Ø-1, word 2, unit 2 = Ø,1,2

2. TCU Invalid Messages per frame when set indicates that an invalid message was received by a TCU

   a. TCU 1 - bit 4, word 2, unit 1
   b. TCU 2 - bit 4, word 2, unit 2

3. Video Bit Errors counts the number of video bit errors that occur per frame - bits Ø-9, word 4, unit 1

III. Range Data is obtained from the Range Measurement Units associated with each TCU which measure the time-of-arrival (TOA) in each TCU-RPV-TCU transmission path.

A. Range 1 - bits 11-15, word 2, unit 1 (Least Significant Bit [LSB] = bit 11)

   - bits Ø-15, word 3, unit 1 (High Order Bit [HOB] = bit 15)

B. Range 2 - bits 11-15, word 2, unit 2 (LSB=bit 11)

   - bits Ø-15, word 3, unit 2 (HOB=bit 15)

C. Range 3 - bits 11-15, word 4, unit 1 (LSB=bit 11)

   - bits Ø-15, word 4, unit 2 (HOB=bit 15)

IV. Data is available from the interface when the ready flag is set - bit Ø, word 1, unit 1.

2.2.2. Data Processing

The data is read asynchronously once per frame (1/30 second) from the interface using interrupts from the programmable clock. The validity of the data is assured by testing the READY flag before data is read from the interface. This is set except when new data is being transferred to the interface. Normally the READY flag is set and the eight interface words are read one at a time. The READY flag is tested again after each read and if it has gone down, the word is reread until the flag comes up. If the initial test shows that the READ flag is down, a loop is entered which continually checks the flag for

Unit 1

Bits	Word 1	Word 2	Word 3	Word 4
0	Ready Flag	TCU 1 Accepted		
1		Messages per Frame		
2	RPV 1 Parity	TCU 3 Search/TRK		
3	Errors per	TCU 3 Alarm		
4	Frame	TCU 1 Invalid Frame		Video Bit
5		Blank		Errors per
6		TCU 1 Alarm/TRK		Frame
7	RPV 1 Accepted	TCU 1 Search	TOA	
8	Messages per	RPV 1 Locked/UNLK	#1	
9	Frame	RPV 1 Acknowledge		
10		RPV 1 Search		Blank
11	RPV 1 Search			
12	Mode	TOA		TOA
13		#1		#3
14	RPV 1 Data Rate			
15				

Table 3

Input Format WCCM Interface

	Bits	Word 1	Word 2	Word 3	Word 4
Unit 2	0	Blank	TCU 2 Accepted Messages per Frame		
	1				
	2	RPV 2 Parity	Blank		
	3	Errors per	Blank		
	4	Frame	TCU 2 Invalid Frame		
	5		Blank		
	6		TCU 2 Alarm		
	7	RPV 2 Accepted	TCU 2 Search/TRK	TOA	TOA
	8	Messages per	RPV 2 Locked/UNLK	#2	#3
	9	Frame	RPV 2 Acknowledge		
	10		RPV 2 Search		
	11	RPV 2 Search			
	12	Mode	TOA		
	13		#2		
	14	RPV 2 Data Rate			
	15				

Table 3

Input Format WCCM Interface (Continued)

a period of one millisecond which is the time it takes for new data to be put into the interface. If the READY flag comes up, the data is read normally. Otherwise, the message code to display INTERFACE NOT READY is set and the data from the interface is read anyway.

The data bits are extracted from the interface words under the following conditions:

(1) No data is analyzed for a TCU/RPV combination if the TCU alarm bit is set.

(2) If a TCU or RPV is searching, the Accepted Messages and the Invalid Message data are not analyzed.

(3) If RPV 1 is unlocked, the range data is not analyzed.

(4) In the V&T mode, the video bit errors are analyzed only if a master reset has been done.

If a TCU or RPV drops out of track into search, the appropriate message TCU, SEARCH, REACQUIRE? or RPV SEARCH, REACQUIRE? is displayed. The time that is taken in the TCU and RPV search modes is monitored and if the time exceeds 3.5 minutes the message TCU SEARCH FAIL, TXFER? or RPV SEARCH FAIL, RATE? is displayed.

The statistical data, RPV Accepted Messages per frame, RPV Parity Errors per frame, TCU Accepted Messages per frame, TCU Invalid Message, and Video Bit Errors per frame, are averaged each second and displayed in Area 1. The track/search status, the RPV unlock/locked status, and any TCU alarms are also displayed.

2.3. COMMANDS

The commands used to operate the WCCM Automated Test Facility are displayed in Area 3 which is light pen sensitive. A command is chosen by sensing the desired main button with the light pen. After the command is ACCEPTed any appropriate sub-buttons are displayed for selection in the right hand column of Area 3. Some commands cause questions to be displayed in Area 2 which require that YES or NO be sensed in Area 3. This ensures that the operator is aware of particular conditions pertaining to the execution of these commands.

The steps which are taken by the routines in the execution of the commands are outlined below:

1. A main button hit when accepted causes the command interpreter routine to select the command code and to initiate the blinking of the main button. If no sub-buttons are required, the command code followed by a zero is put on the command stack for step 3. Otherwise a menu of sub-buttons is displayed in Area 3.

2. A sub-button hit when ACCEPTed tells the command interpreter to determine the desired parameter code or value. The command code followed by the parameter is then put on the command stack.

3. The command output routine takes the code from the command stack and checks the appropriate constraints. If these are satisfied, the command and the accompanying parameter, if there is one, are translated into the correct bits and put into the right output interface word. A completion code is also put on the display stack. If the constraints are not satisfied, the command is not executed and a code for either a terminal message or a question is put on the display stack.

4. The display update routine takes one of three actions depending on the code sent by the command output routine.

   a. Completion code: The main button is stopped from blinking and any menu options are taken down from the screen.

   b. Terminal message: Any previous message is scrolled upward in Area 2 and a new phrase which is indicative of the problem is set blinking at the bottom. The actions described in (a) are also performed.

   c. Question: A question is displayed blinking at the bottom of Area 2 after the previous messages are scrolled up. The menu options are replaced by the YES and NO buttons.

5. A YES or NO hit is encoded by the command interpreter and put on the command stack.

6. The command output routine tests the validity of the reply and executes step (3) if all questions have been answered so that all the constraints have been satisfied. If a further question remains for the command under consideration, the proper code is put on the display stack for step (4). If the answer to the question is such that the command should not be executed, a code for the appropriate terminal message is placed on the display stack for step (4) to display.

A description of the WCCM commands is given in Table 4. A complete list of the messages which appear in Area 2 is explained in Table 5. These two tables also set forth the constraints which are maintained over the commands.

Copies of the various commands which have been performed are retained in core. These are used to analyze the status data, to input the fake scenario data in an orderly fashion, and are also recorded if the data recording mode has been selected. The locations of the various commands on the output interface are shown in Table 6.

Table 4 WCCM Command Summary

Command	Button	Sub-Button	Action
Exit	*EXIT		Exit to RT-11 Monitor
Restart	*RESTART		Restart first overlay (initialization)
New Screen Center	*SET CENTER	*CENTER	Resets center of Area 4 of GT to point indicated by the light-pennable cursor
Clear	*CLEAR		Clears outputs to WCCM hardware
Master Reset	*MASTER RESET		Resets all WCCM PN generators
TCU 1 Time Assignment	*T1= ___	Sliding Scale 0 - 999	Sets TCU1 time assignment to value indicated unless TCU2 or TCU3 already has that value
TCU 2 Time Assignment	*T2= ___	Sliding Scale 0 - 999	Sets TCU2 time assignment to value indicated unless TCU1 or TCU3 already has that value
TCU3 Time Assignment	*T3= ___	Sliding Scale 0 - 999	Sets TCU3 time assignment to value indicated unless TCU1 or TCU2 already has that value
Set Timing Transfer Word	*TXFER= ___	Sliding Scale 0 - 999	Sets timing transfer value to be used for the PN RESET command
Transmit RPV 1 PN LOCK or UNLOCK	*LOCK1/*UNLOCK1	*UNLOCK *LOCK	The UNLOCK or LOCK command which was sensed is set
Transmit RPV 2 PN LOCK or UNLOCK	*LOCK2/*UNLOCK2	*UNLOCK *LOCK	The UNLOCK or LOCK command which was sensed is set

Table 4 WCCM Command Summary (Cont'd)

Command	Button	Sub-Button	Action
TCU 1 Mode	*TCU1=___	*CT	Sets TCU1 mode to continuous telemetry if all other TCU's are OFF
		*V&T	Sets TCU1 mode to video and telemetry if all other TCU's are OFF
		*TDMA	Sets TCU1 mode to time division multiple access
		*OFF	Sets TCU1 mode to OFF
TCU 2 Mode	*TCU2=___	*CT	Sets TCU2 mode to continuous telemetry if all other TCU's are OFF
		*V&T	Sets TCU2 mode to video and telemetry if all other TCU's are OFF
		*TDMA	Sets TCU2 mode to time division multiple access
		*OFF	Sets TCU2 mode to OFF
TCU 3 Mode	*TCU3=___	*CT	Sets TCU3 mode to continuous telemetry if all other TCU's are OFF ‡
		*V&T	Sets TCU3 mode to video and telemetry if all other TCU's are OFF ‡
		*TDMA	Sets TCU3 mode to time division multiple access
		*OFF	Sets TCU3 mode to OFF
Reset TCU PN Generators	*PN RESET	*TCU1 *TCU2 *TCU3	Resets the PN Generator of the TCU which was sensed if the value of the timing transfer word is correct

‡ Not applicable in current configuration.

Table 4 WCCM Command Summary (Cont'd)

Command	Button	Sub-Button	Action
Set Data Rates	*RPV,GCS DATA RATE=___	*12 *15 *20 *24 *30 *40 *60 *120	The RPV and GCS are set to the data transfer rate sensed if the value does not conflict with the number of RPV's (= manual cycle input). See Table 1.
Initiate TCU 1	*INITCU1		Initiates execution of all TCU1 and RPV1 commands if the TCU1 time assignment is correct and desired RPV1 LOCK/UNLOCK condition is set
Initiate TCU 2	*INITCU2		Initiates execution of all TCU2 and RPV2 commands if the TCU2 time assignment is correct and the desired RPV2 LOCK/UNLOCK condition is set
Set RPV Altitude	*ALTITUDE (/100)=___	Sliding Scale 0 - 400	Sets RPV altitude for the bilateration and relateration scenarios in units of hundreds of feet
Wrong RPV Position	*RPV POSIT WRONG		The other solution for the RPV coordinates is selected for display
Set data recording parameters	*RECORD=___	*RAW	Use a sliding scale to choose a raw data sample rate from 1 in 1 to 1 in 100
		*AVERAGE	Use a sliding scale to choose an averaged data sample rate from 1 in 1 to 1 in 100

Table 4 WCCM Command Summary (Cont'd)

Command	Button	Sub-Button	Action
Set data recording parameters (Cont'd)		*RAWOFF	Disable recording of raw data
		*AVGOFF	Disable recording of averaged data
		*RUN	Open file and record data as selected above
		*STOP	Stop data recording and close file

Table 5 Description of Informational Messages Displayed at Various Times in Area 2

a.) COMMAND ABORT, ALARM IF CHANGED

A TCU mode was chosen which is incompatible with other TCU modes. Command ignored.

b.) COMMAND ABORT, RATE/# RPV

A data rate was chosen which is incompatible with the number of RPV's previously designated. Command ignored.

c.) COMMAND ABORT, TIME CONFLICT

A time assignment was chosen which is the same as a previous time assignment. Command ignored.

d.) COMMAND ACKNOWLEDGE

A link command acknowledge was received from an RPV after a TCU initiate command was executed.

e.) XXX DESIRED TIMING XFER?

Is the specified timing transfer the desired value? The operator must sense either the YES or NO light button.

f.) EXECUTE LOCK/UNLOCK

The current RPV lock/unlock condition was unacceptable. The operator should choose the desired condition.

g.) EXECUTE TIME ASSIGN

The current TCU time assignment was unacceptable. The operator should choose the desired time assignment.

h.) EXECUTE TIMING XFER

The current timing transfer word was unacceptable. The operator should choose the desired timing transfer value.

i.) INTERFACE NOT READY

A millisecond long attempt to read the WCCM interface failed because the READY FLAG was not set. The data was read anyway. This message is displayed at the end of the second in which the failure occurred.

Table 5 Description of Informational Messages
Displayed at Various Times in Area 2
(Cont'd)

j.) LOCK CONDITION DESIRED?

Is the RPV locked condition desired? The operator must sense either the YES or NO light button.

k.) RCVD RPV RATE NOT = SET RATE

The data rate returned from an RPV is not equal to the rate set at the GCS.

l.) RECORD ABORT, OPEN ERROR

An error occurred while trying to open a disk file for recording. Record command ignored.

m.) RECORD END FILE

An end-of-file was found while recording. No more contiguous disk space is available and the recording file is closed.

n.) RECORD END, I/O ERROR

Recording is terminated due to an I/O error.

o.) RECORD END, TIME OVER-RUN

Recording was terminated when a disk block write was attempted before the previous write was complete.

p.) RPV SEARCH FAIL.RATE?

An RPV search has not resulted in a tracking condition within 3.5 minutes. The operator may need to change the data rate.

q.) RPV SEARCH.REACQUIRE?

A tracking RPV has reverted to the search condition. If the uplink is not reacquired, a MASTER RESET should be executed.

r.) TCU SEARCH FAIL.TXFER?

A TCU search has not resulted in a tracking condition within 3.5 minutes. The operator may have to change the timing transfer word.

Table 5 Description of Informational Messages
Displayed at Various Times in Area 2
(Cont'd)

s.) TCU SEARCH.REACQUIRE

A tracking TCU has reverted to the search condition. If the down link is not reacquired, a PN RESET should be executed.

t.) TDMA CONTENTION

TCU ALARM bits are set because the TDMA time assignments are too close together.

u.) XXX TIME ASSIGN CORRECT?

Is the specified time assignment the correct value? The operator must sense either the YES or NO light button.

v.) UNLOCK CONDITION DESIRED?

Is the RPV unlocked condition desired? The operator must sense either the YES or NO light button.

Unit 1

Bits	Word 1	Word 2	Word 3	Word 4
0				
1			RPV	
2			Data Rate	
3				
4	Timing	RPV 1		RPV 3
5	Transfer	Time	GCS (TCU)	Time
6	Word	Assignment	Data Rate	Assignment
7				
8				
9				
10				
11				
12		TCU 1		
13		Mode		
14	TCU 1 Initiate	RPV 1 PN Lock		
15	TCU 2 Initiate			

Table 6

Output Format WCCM Interface

Unit 2

Bits	Word 1	Word 2	Word 3	Word 4
0			TCU 1 PN Reset	
1			TCU 2 PN Reset	
2			TCU 3 PN Reset	
3			Master Reset	
4		RPV 3	TCU 3	
5		Time	Mode	
6		Assignment		
7				
8				
9				
10				
11				
12		TCU 2		
13		Mode		
14		RPV 2 PN Lock		
15				

Table 6

Output Format WCCM Interface (Continued)

2.4. RPV LOCATION

The algorithms used to determine the position of the RPV for the tri-lateration, bi-lateration, and relateration scenarios are derived in the Appendix. The form of the Kalman filter used to maintain a location accuracy of 3 meters is also derived.

If RPV 1 is locked, the range data is extracted from the interface every tenth of a second and the position calculations are performed. The RPV X,Y,Z coordinates and its range, R, are filtered. Each second, in addition to finding X,Y,Z, and R, the RPV speed, altitude, bearing, and heading are computed. Area 4 which shows the RPV location graphically and Area 5 which gives the current RPV location data are also updated at this time.

In certain situations the RPV location which is calculated will be incorrect. The command button *RPV POSIT WRONG is provided so that the operator can select the other possible RPV position. Two solutions occur due to a square root term (see Appendix) which is always obtained in the algorithms developed for each of the scenarios. Lack of both core space and computation time precluded the development of a method for distinguishing the correct solution.

2.5. DISPLAY MANIPULATION

The creation of displays is accomplished basically by the manipulation of two buffer areas. The first, VTBUFF, is in the named .CSECT "DSPBFR". This area contains the display instruction codes that are interpreted by the display processor hardware. The first word in VTBUFF is a display no-op (DNOP) followed by a series of display instruction codes for the creation of each of the graphics on the screen. These are followed by a display jump instruction (DJMP) which causes the display hardware processor to jump back to the beginning of VTBUFF to repeat the refresh cycle. The format of VTBUFF is then:

VTBUFF:	DNOP
	Graphic 1
	Graphic 2
	⋮
	Graphic N
	DJMP
	Addrs of VTBUFF

The general format of a graphic inserted in VTBUFF has a "POINT" mode display instruction first followed by the initial X and Y coordinates and the specific display codes for the graphic being displayed. The "POINT" instruction normally has the light pen off (LPOFF), blink off (BLKOFF), and line type

Ø (LINEØ, unbroken line) bits set. These functions may then be individually controlled for each graphic; i.e., to blink a graphic the appropriate bits can be set in the initial "POINT" instruction while the following graphics will remain not blinking. The format of a graphic within VTBUFF is:

POINT + LPOFF+ BLKOFF + LINEØ
Screen X coord
Screen Y coord
Specific graphic codes

The second buffer used to control displays is the ID table (IDTBL), also in .CSECT DSPBFR. Through the manipulation of this table, individual graphics can be assigned an ID which can then be used to address that graphic in VTBUFF. With this facility graphics can be enabled for light pen hits and light pen hits on the screen can be identified. Also, graphics can be blinked, unblinked, disabled for light pen hits, deleted from the display, and modified by addressing their IDs. The format of IDTBL has a two-word entry for each of 256 possible IDs (0-255). The first word is the index into VTBUFF for the graphic (the index is in the FORTRAN sense; i.e., 1=1st word, 2=2nd word, etc.). The first byte of the entry's second word is the length of the graphic (255 words maximum) and the second byte is the ID. That is,

Index	
ID	graphic length

ID number Ø is reserved for the tracking cross, IDs 1-255 are general purpose.

The standard RT-11 display handler is used only to start the display in the initialization process. Once the VT11 processor begins refreshing the display from VTBUFF the RT-11 display handler is replaced by a much simpler and smaller processor generated for the WCCM system. This processor uses only a small fraction of the memory space required by the RT-11 display processor and also provides a flicker-free display for a larger number of graphics.

2.6. RECORDING

The operator may record the data on disk by sensing the *RECORD light button. Either raw data from the interface or the data averaged over one second as displayed in area 1 and area 5 or both may be recorded. The sample rate for each type of data may be varied from 1 in 1 to 1 in 100. A block of raw data is available every thirtieth second and a block of averaged data, every second. As many as 100 recording data files may be stored on disk. This is accomplished by naming the files as follows: DK1.WCCMØØ.DAT-DK1.WCCM 99.DAT. When the recording function is selected, a search is made of the DK1 directory and the first available file is opened. This name is displayed at the bottom center of area 2 (See Figure 1). The time which remains before the allocated disk space is filled is shown at the bottom right of area 2. The format is MINUTES:SECONDS. The time is appropriately decremented as recording proceeds. The data format is summarized in Table 7. The header shows the state of the system when recording was initiated. Raw and averaged data are recorded according to the selected sample rate. Commands which are executed during recording are encoded and recorded. Parameters which were set are also included, e.g., the data rate, etc. The recording of data may be terminated at any time. Any errors which occur cause a message to be displayed in area 2 for the information of the operator. These messages are described in Table 5.

2.7. SCENARIO GENERATION

A separate FORTRAN program was written to generate simulated status data from the WCCM hardware and range data for either the trilateration and bilateration scenarios or the relateration scenario. There were several reasons for the scenario generator. It allowed almost all the program development to take place at the PAR facility. It was possible to demonstrate all three scenarios without using the WCCM hardware, which is not currently configured to provide range data for any of the scenarios. It allowed complete testing of the RPV location routines so that the algorithms could be debugged and their performance optimized.

The parameters necessary for scenario generation are now described. The RPV Parity Errors per frame are entered as the fraction of errors desired and the standard deviation of the distribution of these errors. If the deviation is zero, the specified fraction is fixed. Otherwise the parity errors are calculated to follow a Gaussian distribution. Each number is converted to a percentage value. When scenario data is read this number is converted to parity errors per frame according to the data rate specified and the number of RPVs (see Table 1). The RPV Accepted Messages per frame is found by subtracting the parity errors per frame from the total number of possible messages. The TCU Accepted Messages per frame is entered as a fraction. If the fraction is positive the value is normalized to obtain 0, 1, or 2. If the resulting value is less than 2 the invalid message bit is set. If the fraction entered is negative, a random number is found for each frame. If this number is more than the absolute value of the fraction, two accepted messages per frame are

Table 7 Data Format of WCCMXX.DAT Files

Block	Word #	Format	Description
Header	1	Integer*2	1 = header code
	2	Integer*2	Day
	3	Integer*2	Month
	4	Integer*2	Year
	5	Integer*2	Hours (24 hour clock)
	6	Integer*2	Minutes
	7	Integer*2	Seconds
	8	Integer*2	Sixtieths of a Second
	9	Integer*4	Cumulative Sixtieths
	11	Integer*2	Scenario Code (0=Status Only; 1=Trilateration; 2=Bilateration; 3=Relateration)
	12	Integer*2	# of RPV's
	13	Real*4	GCS #1 X (km)
	15	Real*4	GCS #1 Y (km)
	17	Real*4	GCS #1 Z (km)
	19	Real*4	GCS #2 X (km)
	21	Real*4	GCS #2 Y (km)
	23	Real*4	GCS #2 Z (km)
	25	Real*4	GCS #3 X (km)
	27	Real*4	GCS #3 Y (km)
	29	Real*4	GCS #3 Z (km)
	31	Real*4	RPV Altitude (km)
	33	Real*4	Kalman Filter Update Error
	35	Integer*4	Range 1
	37	Integer*4	Range 2
	39	Integer*4	Range 3
	41	Integer*4	Range 4
	43	Integer*4	Range 5
	45	Integer*2	Raw Data Sample Interval
	46	Integer*2	Averaged Data Sample Interval
	47	Integer*2	Timing Transfer Estimate
	48	Integer*2	RPV and GCS Data Rate
	49	Integer*2	Master Reset Indicator (0=no reset; 1=searching; -1=tracking)
	50	Integer*2	TCU1 Time Assignment
	51	Integer*2	RPV1 Lock Indicator (0=unlock; 1=lock)
	52	Integer*2	RPV1 Mode (0=OFF; 1=CT 2=V&T; 3=TDMA)
	53	Integer*2	TCU2 Time Assignment
	54	Integer*2	RPV2 Lock Indicator
	55	Integer*2	RPV2 Mode

Table 7 Data Format of WCCMXX.DAT Files (Cont'd)

Block	Word #	Format	Description
Header (Cont'd)	56	Integer*2	TCU3 Time Assignment
	57	Integer*2	Blank
	58	Integer*2	TCU3 Mode
Raw Data	1	Integer*2	2 = header code
	2	Integer*2	Word 1 Unit 1 of Interface
	3	Integer*2	Word 2 Unit 1 of Interface
	4	Integer*2	Word 3 Unit 1 of Interface
	5	Integer*2	Word 4 Unit 1 of Interface
	6	Integer*2	Word 1 Unit 2 of Interface
	7	Integer*2	Word 2 Unit 2 of Interface
	8	Integer*2	Word 3 Unit 2 of Interface
	9	Integer*2	Word 4 Unit 2 of Interface
Averaged Data	1	Integer*2	3 = header code
	2	Integer*2	TCU1 Alarm
	3	Integer*2	TCU1 Track Indicator (0=Search; 1=Track)
	4	Byte*2	TCU1 Accepted Message per Frame
	5	Byte*2	TCU1 Invalid Messages per Frame
	6	Integer*2	RPV1 Search Mode (0=Track; 1=Mode 1; 2=Mode 2; 3=Mode 3; 4-Mode 4)
	7	Integer*2	RPV1 Lock Indicator (0=Unlock; 1=Lock)
	8	Byte*2	RPV1 Accepted Messages per Frame
	9	Byte*2	RPV1 Parity Errors per Frame
	10	Integer*2	RPV1 Data Rate
	11	Integer*2	RPV1 Command Acknowledge
	12	Integer*2	TCU2 Alarm
	13	Integer*2	TCU2 Track Indicator
	14	Byte*2	TCU2 Accepted Messages per Frame
	15	Byte*2	TCU2 Invalid Messages per Frame
	16	Integer*2	RPV2 Search Mode
	17	Integer*2	RPV2 Lock Indicator
	18	Byte*2	RPV2 Accepted Messages per Frame

Table 7 Data Format of WCCMXX.DAT Files (Cont'd)

Block	Word #	Format	Description
Averaged Data (Cont'd)	19	Byte*2	RPV2 Parity Errors per Frame
	20	Integer*2	RPV2 Data Rate
	21	Integer*2	RPV2 Command Acknowledge
	22	Integer*2	TCU3 Alarm
	23	Integer*2	TCU3 Track Indicator
	24	Byte*2	Video Bit Errors per Frame
	25	Real*4	RPV X Coordinate (km)
	27	Real*4	RPV Y Coordinate (km)
	29	Real*4	RPV Z Coordinate (km)
	31	Real*4	RPV Range from Origin (km)
	33	Integer*2	RPV Bearing (degrees)
	34	Real*4	RPV Altitude
	36	Real*4	RPV Speed (km/hr)
	38	Integer*2	RPV Heading
	39	Real*4	Relay X Coordinate (km)
	41	Real*4	Relay Y Coordinate (km)
	43	Real*4	Relay Z Coordinate (km)
Master Reset	1	Integer*2	5 = header code
	2	Integer*2	
Timing Transfer	1	Integer*2	6 = header code
	2	Integer*2	Timing Transfer Value
RPV1 Lock	1	Integer*2	7 = header code
	2	Integer*2	
RPV1 Unlock	1	Integer*2	8 = header code
	2	Integer*2	
RPV2 Lock	1	Integer*2	9 = header code
	2	Integer*2	
RPV2 Unlock	1	Integer*2	10 = header code
	2	Integer*2	

Table 7 Data Format of WCCMXX.DAT Files (Cont'd)

Block	Word #	Format	Description
CLEAR	1	Integer*2	11 = header code
	2	Integer*2	
Initiate TCU1	1	Integer*2	12 = header code
	2	Integer*2	
Initiate TCU2	1	Integer*2	13 = header code
	2	Integer*2	
PN Reset TCU1	1	Integer*2	14 = header code
	2	Integer*2	
PN Reset TCU2	1	Integer*2	15 = header code
	2	Integer*2	
PN Reset TCU3	1	Integer*2	16 = header code
	2	Integer*2	
TCU1 Time Assignment	1	Integer*2	17 = header code
	2	Integer*2	TCU1 Time Assignment Value
TCU2 Time Assignment	1	Integer*2	18 = header code
	2	Integer*2	TCU2 Time Assignment Value
TCU1 Mode	1	Integer*2	19 = header code
	2	Integer*2	TCU1 Mode (0=OFF; 1=CT; 2=V&T; 3=TDMA)
TCU2 Mode	1	Integer*2	20 = header code
	2	Integer*2	TCU2 Mode
TCU3 Mode	1	Integer*2	21 = header code
	2	Integer*2	TCU3 Mode

Table 7 Data Format of WCCMXX.DAT Files (Cont'd)

Block	Word #	Format	Description
GCS, RPV	1	Integer*2	22 = header code
Data Rate	2	Integer*2	Data Rate Code
TCU3 Time	1	Integer*2	23 = header code
Assignment	2	Integer*2	TCU3 Time Assignment Value

specified. Otherwise, another random number is found which is normalized to 0 or 1 for the value of the accepted messages per frame and the invalid frame bit is set. The Video bit errors per frame are found in the same way as the RPV parity errors per frame.

The RPV initial coordinates are specified and also the number of flight legs. For each leg the time in minutes, and the RPV heading in degrees, altitude in kilometers, and speed in kilometers per hour are entered. For each leg the X, Y velocity components, the average X, Y accelerations, and the rate of altitude change are found. The legs are divided into thirtieth-second or one-frame intervals and the X, Y, Z, altitude, range, and time of arrival values are computed. These data are stored on disk with file names which, by convention, vary from DKØ:SCENØØ.DAT to DKØ:SCEN99.DAT. The format of each frame of data is shown in Table 8.

The procedure described above is used for the trilateration and bilateration scenarios. The relateration scenario is similar, except that the X, Y coordinates and the altitude of the relay aircraft have to be entered. The relay location is fixed to simplify data entry and the computations. This, nevertheless, allows the relateration scenario to be fully evaluated.

SECTION 3

USER'S MANUAL

This section comprises the user's manual for the WCCM Automated Test System. The first part gives detailed instructions for the use of both overlays. The second part describes the organization of the software. The procedure which must be followed when any routine is modified is also given.

3.1. SOFTWARE USAGE

This part of the User's Manual describes the operation of the WCCM Automated Test System in the automatic mode. The initialization of parameters in the first overlay and the execution of commands in the second overlay are described. Finally, the entry of parameters for the scenario generator is given.

3.1.1. Initialization (First Overlay)

The first overlay is a file on DKØ named WCCM.SAV. This module is started running by performing a R(UN) WCCM command after the RT-11 monitor has typed a prompting period on the console terminal. The parameter entry is shown in outline form below. Each response required of the operator is underscored and each must be followed by a carriage return (CR).

Message 1: INPUT? (Specify type of input data)

Response A: REAL DATA (from WCCM hardware)

Response B: FAKE DATA (from scenario file)

Errors: None (If any character other than R is typed, F is assumed)

Message 1a: SCENARIO FILE NAME? (specify file name for Response B above)

Response C: *DK?:SCENXX.EXT (? is Ø or 1, XX is in the range ØØ to 99 and EXT is the file extension; DAT is the default)

ERRORS: FILE NOT FOUND (specified file was not found, Message 1a is typed again, and another name is awaited)

Message 2: SCENARIO? (specify scenario type)

Response A: TRILATERATION

Response B: BILATERATION

Response C: RELATERATION

Response D: STATUS ONLY

Errors: None (if any character other than T, B, or R is typed, S is assumed)

Message 3: # of RPV's (= MANUAL CYCLE INPUT)? (specify number of RPV's desired)

Response: XX (XX is in the range 1 to 25; if this number is greater than 1, the Manual Cycle Input switch must be set appropriately).

Errors: RPV # = 1 FOR THIS SCENARIO! (only for STATUS ONLY is more than 1 RPV allowed)

Message 4: GCS X, Y, Z Coordinates (KM.)
#?: XXX.XXX. YYY.YYY ZZZ.ZZZ ok?
(? = 1, 2, 3 for the appropriate GCS and the coordinates are specified to six digits accuracy in units of kilometers).

Response A: (CR) (accepts the coordinates as typed)

Response B: XXX.XXX (TAB) YYY.YYY (TAB) ZZZ.ZZZ (CR)
(specified new coordinates. This means of changing the COORDS.DAT file should always be used when new values for the GCS coordinates are necessary).

Errors: ??? (an invalid character was detected; retype the line again).

Message 5: RPV ALTITUDE (FT./1ØØ)?
(Specify the altitude of the RPV for the Bilateration and Relateration scenarios).

Response: XXX.XX (type the RPV altitude in units of feet divided by 1ØØ.)

Errors: ??? (invalid character detected, retype the value again).

Message 6: DATE? (specify current date; this message is skipped if the current date is already in the system word).

Response: DD-MMM-YY (DD is the day number of the month, MMM is the first three letters of the month, and YY is the final two numbers of the year).

Errors: ??? (invalid character detected, retype the value again)

Message 7: TIME? (Specify current time)

Response: HH:MM:SS (HH is the hour number in the 24-hour clock, and MM and SS are the minute and second numbers).

Errors: ??? (invalid character detected, retype the value again).

This completes the entry of parameters. When this overlay has finished, the coordinates of the GCS's have been saved in a file named DKØ:COORDS.DAT, the display has been set up, and all the data which will be needed by the second overlay has been stored in a file named DKØ:COMMON.DAT. The second overlay is started by means of .CHAIN request to the RT-11 monitor.

3.1.2. Execution (Second Overlay)

The second overlay is a file on DKØ named GALLOP.SAV. This module is started running either by a .CHAIN in the first overlay or a R(UN) GALLOP command on the console terminal. The use of the latter method must be restricted to those instances where none of the parameters specified in the first overlay need to be changed. Note, in particular, that the date and the time will not be correct. The format of the display on the GT is shown in Figure 1. The current status of the RPV and GCS modems is shown in area 1. Informational messages for the operator are displayed in area 2. The current message blinks and is initially located in the lower part of area 2. Additional messages are scrolled up until five messages are shown. Thereafter, the earliest message disappears and the current message blinks in the lower portion of the area. The current time is given in the lower left. When recording data on disk, the file name and time remaining before the file is filled are shown in the lower center and lower right, respectively. Area 3 contains the light pen sensitive command options to control the operation of the WCCM hardware and software. Area 4 shows graphically the GCS locations and the position of the RPV and relay aircraft. The intersection of the crosshairs indicates the origin of the coordinates. At each GT update, scaling is performed to keep each symbol clearly visible. A different screen center may be chosen by using the *SET CENTER command. At the upper right the approximate number of kilometers per inch provides an indication of the scale. The position data for the RPV and relay is given in area 5. The units of the coordinates, range, and altitude are kilometers; the speed, kilometers per hour, and the bearing and heading are in degrees. The type of scenario is shown at the lower left of this area.

The user-system interaction in the second overlay takes place exclusively via the light pen sensitive command buttons in area 3. When a button is sensed the asterisk prefix begins to blink and the *ACCEPT and *REJECT buttons appear in right hand column. No action is taken if *REJECT is sensed with the

light pen. If *ACCEPT is chosen the command is either executed or else various sub-buttons appear in the right-hand column. In all cases an *ACCEPT button must be sensed before any action is taken by the system. The exception is the *SET CENTER command which accepts the cursor location immediately when the *CENTER button is hit. Several of the command buttons are followed by an = symbol and a quantity or a parameter. This indicates the current condition of that particular command. The WCCM commands are described in Table 4. Choosing the appropriate data rate is aided by Table 1, especially if the number of RPV's is greater than one. Table 2 helps to choose the appropriate time assignments. Contention will be avoided in the TDMA mode by accounting for the range differential between the RPV modems, the number of RPV modems, and duration of the TDMA burst.

The sequence of events which enables the WCCM modems to achieve code synchronization is presented below:

I. Set TCU's to desired mode - at least one TCU must be in a mode other than OFF. The only mode which supports multiple TCU's is TDMA.

II. Set appropriate timing assignments for TCU's, (meaningful only for the TDMA mode).

III. Set Data Rate - This must be consistent with the RPV number. See Table 1.

IV. Initiate TCU's as necessary - This causes the WCCM hardware to execute the commands specified in the previous three steps. Only the RESET commands do not require an INIT to be done before a command is executed.

V. Master Reset - Resets the three TCU and the GCS transmit PN generators so that the system timing may be referenced to the GCS transmit frame mark. The GCS is now transmitting a spread spectrum waveform to the RPV modems which begin advancing and retarding the PN sequence position with respect to the initial PN generator state for code synchronization. There are four RPV search modes:

Mode 1 searches over ± 320 chips for up to 6.4 seconds.
Mode 2 searches over ± 1280 chips for up to 32 seconds.
Mode 3 searches over ± 5130 chips for up to 135 seconds.
Mode 4 searches over ± 1,000,000 chips for up to 33 seconds.

If the RPV modems do not enter the track mode within 3.5 minutes, either the communications channel does not have a sufficient signal-to-noise ratio or there is a hardware fault.

VI. Set RPV's to LOCK

VII. Initiate TCU's - This action locks the RPV transmit frame reference to the GCS receive frame reference and resets the RPV transmit PN generator.

VIII. Set a Timing Transfer estimate to the estimated round-trip propagation delay for a specific TCU. One unit corresponds to 8.333 microseconds or a total distance of 2.5 km.

IX. Initiate specific TCU - This offsets the GCS receive PN generator from the GCS transmit frame mark by the selected time interval.

X. PN RESET for specific TCU. This causes the TCU to start searching as described for MASTER RESET. There is no Mode 4 search in this case, so to achieve timing acquisition, the timing transfer estimate must be known to 4 km for Mode 1, 16 km for Mode 2 or 64 km for Mode 3. If tracking does not occur within three minutes, steps VIII, IX, and X should be repeated with a new timing transfer estimate. It is permissible to allow the software to monitor the WCCM hardware in the manual mode. The pertinent RESETS should be performed so that the appropriate software flags are set. The correct data rate should also be set.

As the commands are executed, the status of the RPV's and TCU's is displayed in area 1. This allows the operator to monitor the operation of the modems. In addition, various messages appear in area 2 which indicate constraints on the commands or inform the operator of various possible errors. Each of the messages is fully described in Table 5.

3.1.3. Scenario Generation

The scenario generator is contained in a file on DKØ named SCENAR.SAV. It is started running by typing R(UN) SCENAR. The parameter entry is again shown in outline form.

Message 1: ENTER Ø FOR TRI- AND BI-LATERATION: 1 FOR RELATERATION!

Integer Response: Ø or 1 as desired

Message 2: RANDOM NUMBER SEEDS (2I5)?

Integer Response: I1, I2 as desired (this provides variable start-up values for the random number generator)

Message 3: RPV #? PARITY ERRORS (PERCENTAGE AND DEVIATION)? (? = 1 and 2)

Floating Response: P,D (P is the desired percentage of RPV Parity Errors per frame expressed as a fraction, e.g., Ø.5. If D=Ø, P is fixed. Otherwise D is taken to be the standard deviation of a Gaussian distribution with mean P)

Message 4: TCU #? ACCEPTED MESSAGES (PERCENTAGE)? (?=1 and 2)

Floating Response: P (P is the desired percentage of TCU Accepted Messages per frame expressed as a fraction, e.g., 1.Ø. If P is positive, the value is specified as Ø, 1, or 2 according to whether P is Ø.5, less than, greater than Ø.5, or equal to 1. If P is negative, a random number is calculated so that after a number of passes the averaged fraction of TCU Accepted Messages per frame approaches P.

Message 5: VIDEO BIT ERRORS (PERCENTAGE AND DEVIATION)?

Floating Response: P,D (see description of response to Message 3)

Message 6: RELAY X, Y, A COORDINATES (KM)? (Relateration scenario only)

Floating Response: X, Y, A (X, Y are the X, Y coordinates and A is the altitude of the relay aircraft in units of kilometers)

Message 7: INITIAL RPV X, Y, A COORDINATES (KM)?

Floating Response: X, Y, A (X, Y are the X, Y coordinates and A is the altitude of the RPV in units of kilometers)

Message 8: NUMBER OF FLIGHT LEGS (37 MAX)?

Integer Response: N+1 as desired

Message 9: LEG#, TIME (MIN), HEADING (DEG), ALTITUDE (KM), SPEED (KPH)

Floating Response: ? T, H, A, S (? = Ø, 1, ..., N, T is the end time of the leg in minutes, H is the RPV heading in degrees, A is the RPV altitude in kilometers, and S is the RPV speed in kilometers per hour. These must be specified for the initial value and each succeeding leg until N+1 lines have been entered.)

Message 10: # BLOCKS = XXX (XXX is the number of blocks of disk space required for the RPV flight specified)

Message 11: SCENARIO FILE NAME:

Alpha Response: *DK?:SCENXX.EXT (where ? is Ø or 1, XX is in the range ØØ to 99, and EXT is the file extension. DAT is the default value.)

Errors: NO CHANNEL AVAILABLE! (monitor fault)
NO ROOM ON DISK! (Compress disk and delete other files to make room. The scenario generator must then be run from the beginning.)

Message 12: DEVIATIONS OF COMPUTED RANGES (X)? (X = 3 or 5 for tri- and bi-lateration or relateration)

Response: D1, D2, D3, D4, D5 (three or five values are entered according to whether tri- and bi-lateration or relateration is the desired scenario. If non-zero, the computed ranges have zero-mean Gaussian noise components added which have the specified standard deviations in units of meters.

Upon completion of the parameter entry, the scenario generator computes status and range data from the RPV at one frame (1/30 second) intervals. These data are stored in the specified scenario file in the format shown in Table 8.

3.2. PROGRAMMING CONSIDERATIONS

This part of the User's Manual gives a brief description of the manner in which the software routines for the WCCM Automated Test System are organized. A brief description is given of the routines which perform the arithmetic operations. Finally, instructions for assembling each routine and for linking all the routines together are given.

3.2.1. Software Organization

The manner in which the routines which comprise the initialization or first overlay are organized is depicted in Figure 2. The dotted lines indicate the different routine file names which are given. The entry points are shown for each routine as well as a brief description of its function. In a similar fashion, the execution or second overlay is shown in Figure 3 and the programmable clock interrupt service, in Figure 4.

Detailed descriptions of the routines are provided in the listings for each program file. The interested reader is urged to study the pertinent listings before any modifications to any routines are attempted.

3.2.2. Arithmetic Operations

The 11/40 computer as currently configured in the GT-44 system does not include the Extended Instruction Set (EIS) option (KE11-E) or the Floating

Bits	#1	#2	#3	#4
0	RPV 1 Parity	RPV 2 Parity		
1	Errors per	Errors per		
2	Frame (%	Frame (%		
3	of total)	of total)		
4				
5				
6				
7				TOA
8				#1
9				(HOB)
10	TCU 1 Accepted Messages per	TCU 2 Accepted Messages per		
11	Frame	Frame		
12			TOA	
13			#1	
14	TCU 1 Invalid Frame	TCU 2 Invalid Frame	(LSB)	
15				

Table 8

Data Format of Scenario File for Thirtieth Second Segments

Bits	#5	#6	#7	#8
0				
1				
2				
3				
4			Video Bit	
5			Errors per	
6			Frame	
7		TOA		TOA
8		#2		#3
9		(HOB)		(HOB)
10				
11				
12	TOA		TOA	
13	#2		#3	
14	(LSB)		(LSB)	
15				

Table 8

Data Format of Scenario File for Thirtieth Second Segments (Continued)

	Data Format of Scenario File for Thirtieth Second Segments			
Bits	#9	#10	#11	#12
0				
1		TOA		TOA
2		#4		#5
3		(HOB)		(HOB)
4				
5				
6				
7	TOA		TOA	
8	#4		#5	
9	(LSB)		(LSB)	
10				
11				
12				
13				
14				
15				

Table 8

Data Format of Scenario File for Thirtieth Second Segments (Continued)

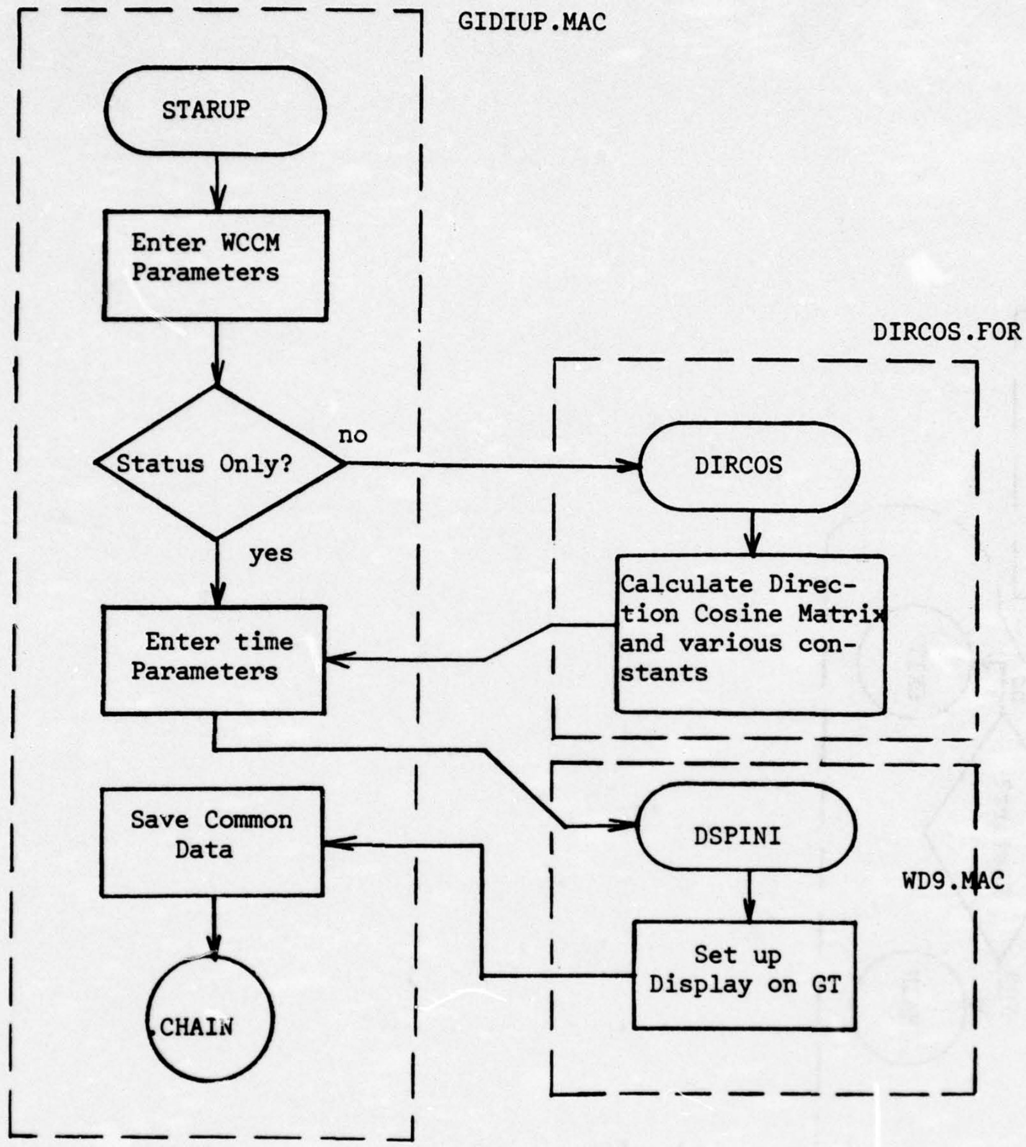
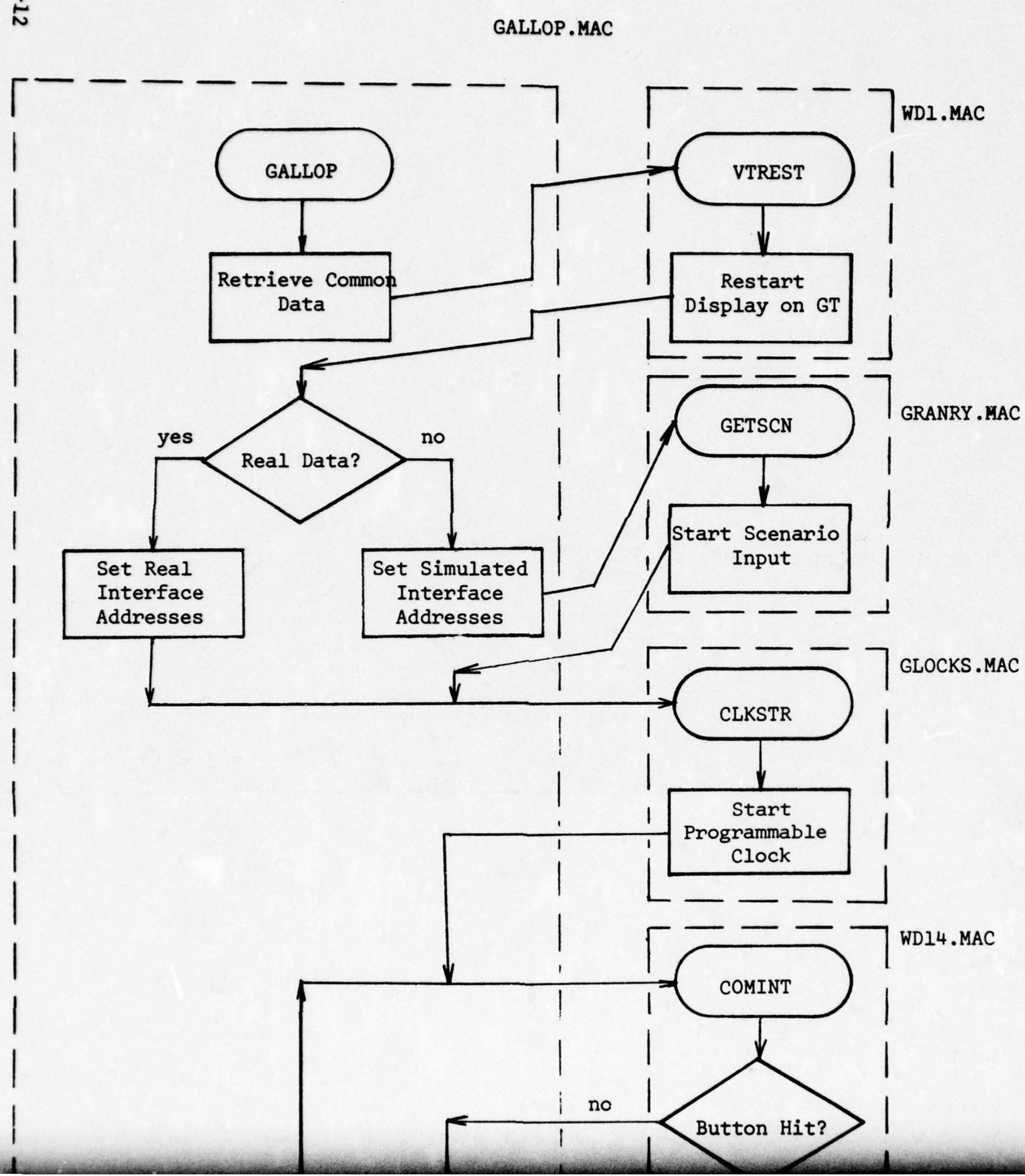
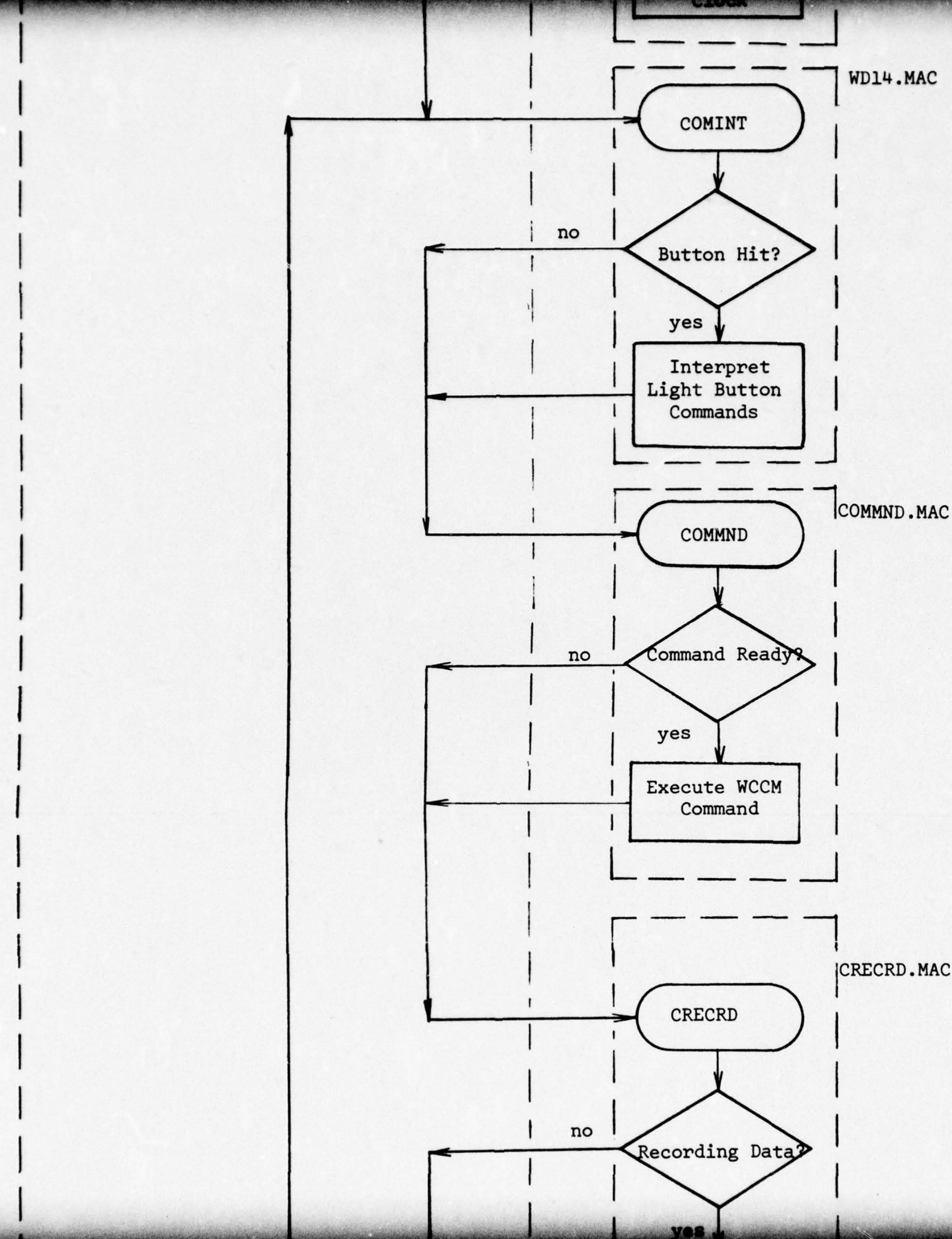


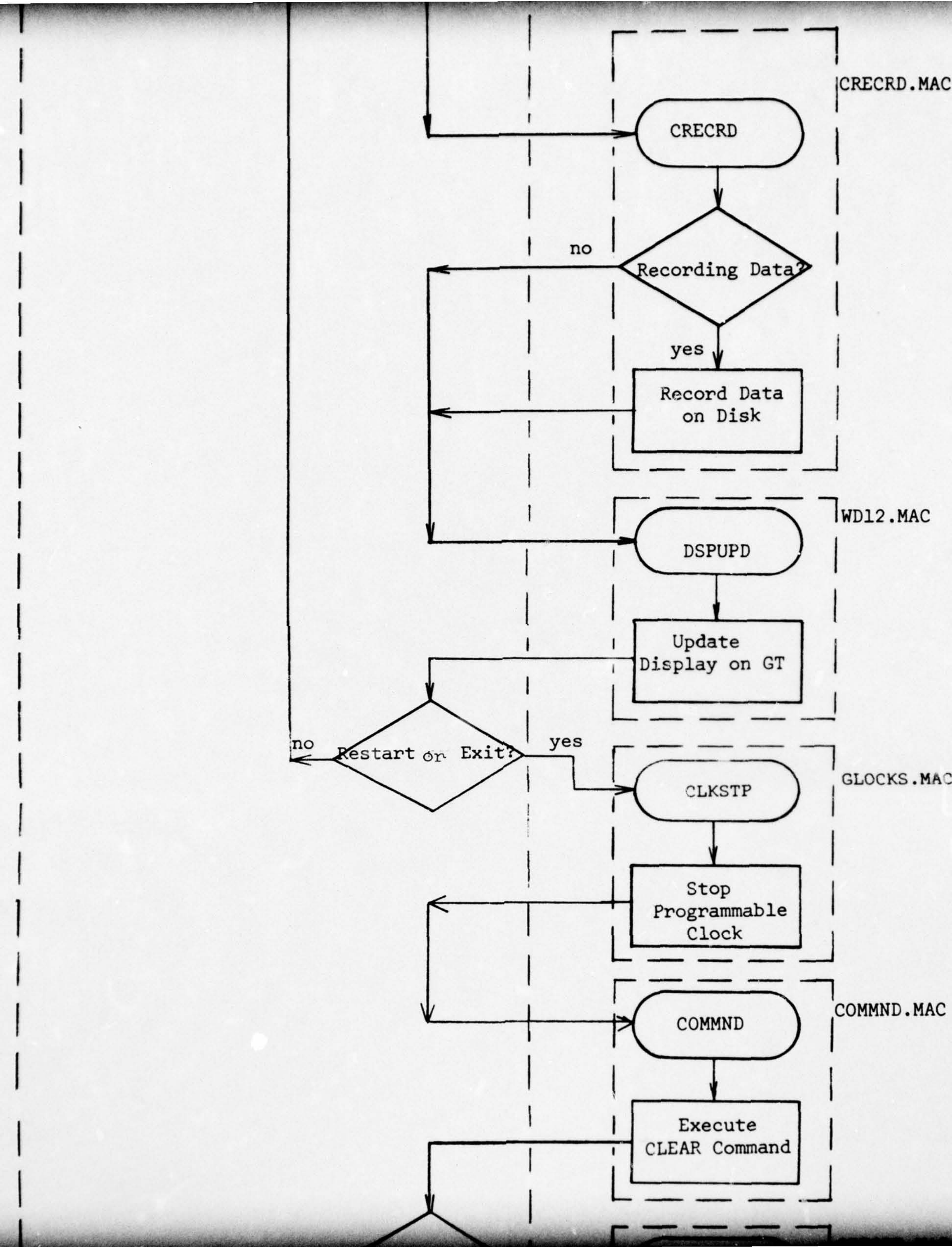
Figure 2 Initialization

Figure 3 Execution



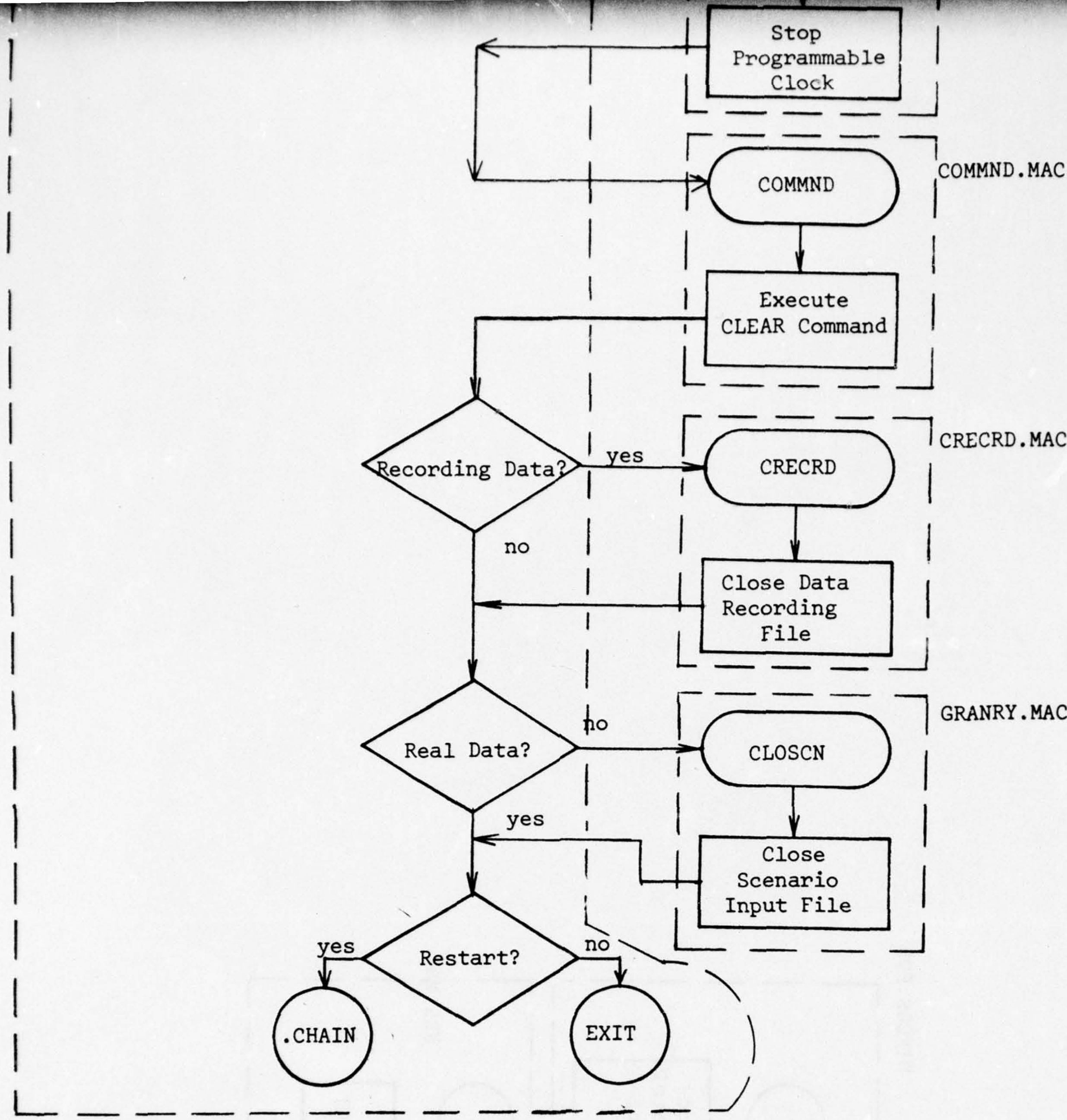

WD14.MAC
COMINT
Button Hit?
no
yes
Interpret Light Button Commands
COMMND.MAC
COMMND
Command Ready?
no
yes
Execute WCCM Command
CRECRD.MAC
CRECRD
Recording Data?
no
yes

2



CRECRD.MAC
CRECRD
Recording Data?
no
yes
Record Data on Disk
WD12.MAC
DSPUPD
Update Display on GT
Restart or Exit?
no
yes
GLOCKS.MAC
CLKSTP
Stop Programmable Clock
COMMND.MAC
COMMND
Execute CLEAR Command

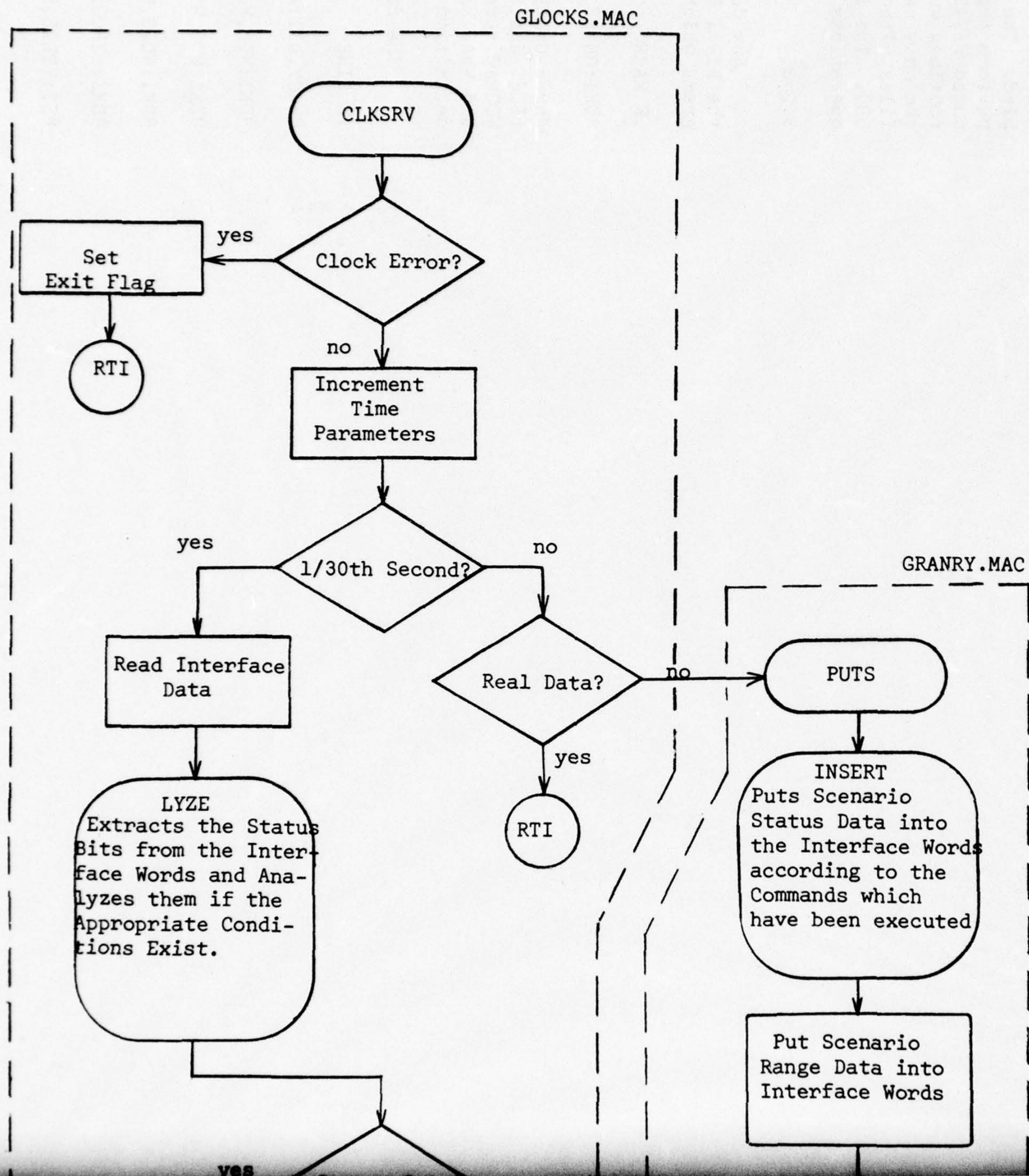
3

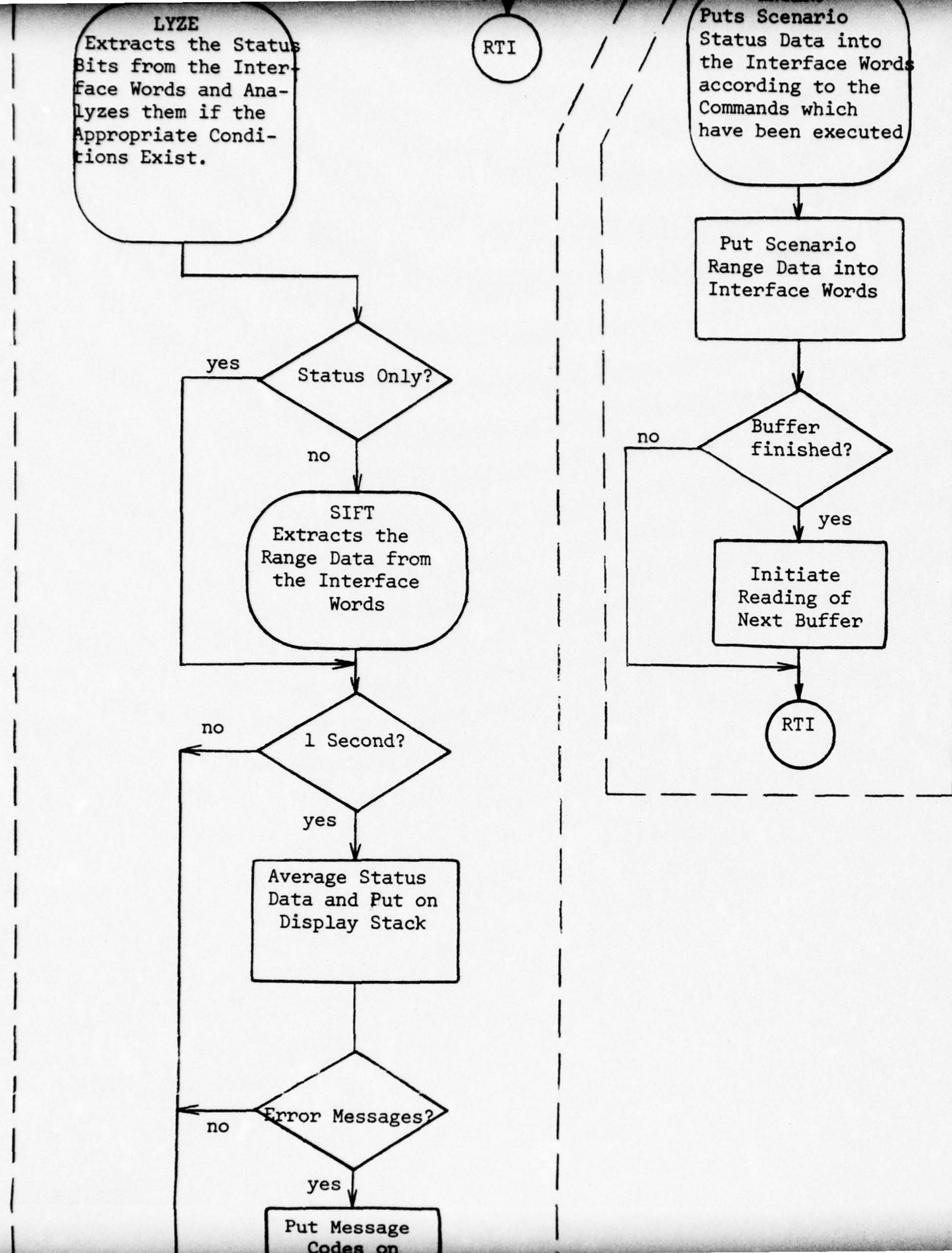


Stop Programmable Clock
COMMND.MAC
COMMND
Execute CLEAR Command
CRECRD.MAC
Recording Data?
yes
no
CRECRD
Close Data Recording File
GRANRY.MAC
Real Data?
no
yes
CLOSCN
Close Scenario Input File
Restart?
yes
no
.CHAIN
EXIT

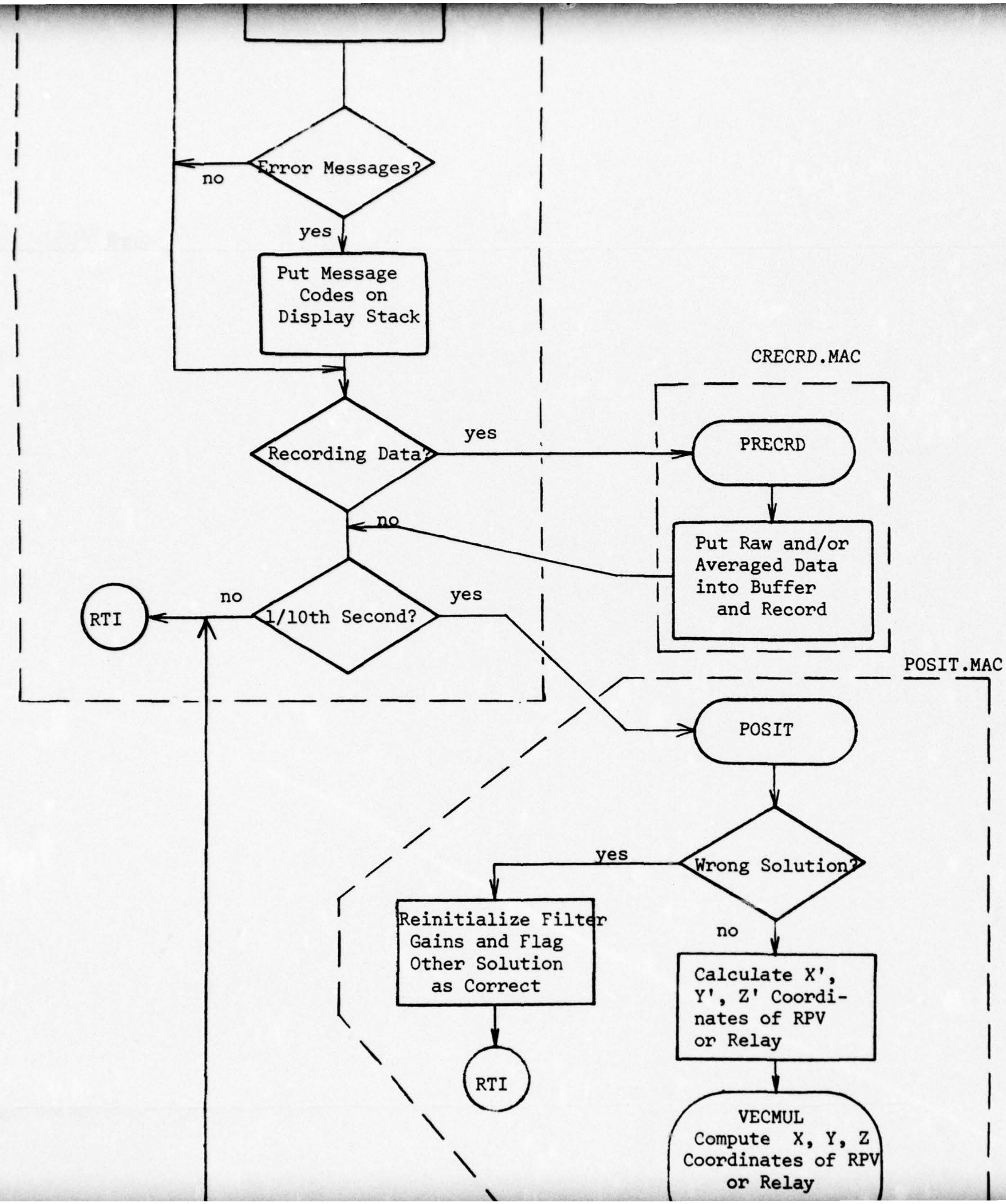
4

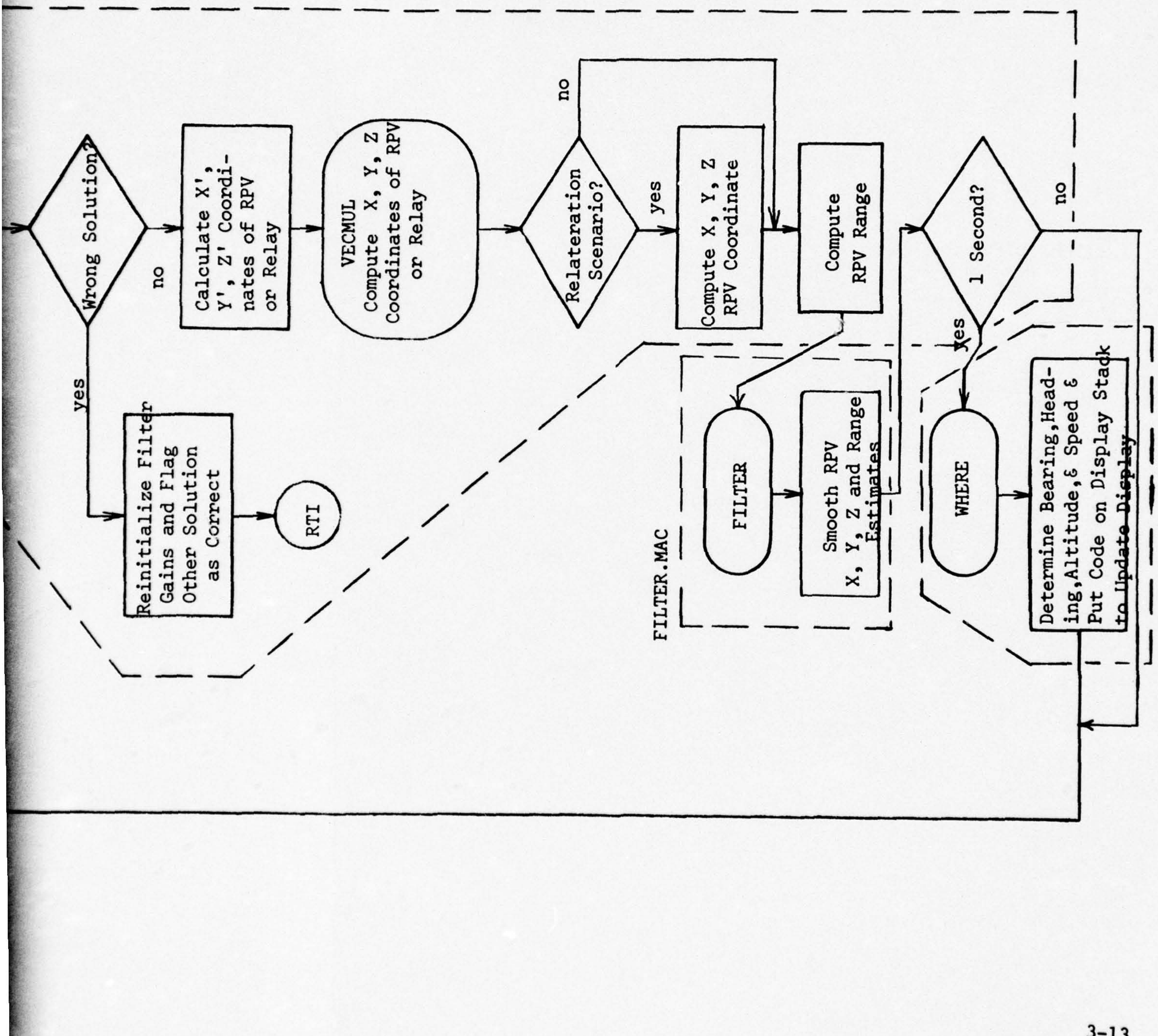
Figure 4 Programmable Clock Interrupt Service




LYZE
Extracts the Status Bits from the Interface Words and Analyzes them if the Appropriate Conditions Exist.
RTI
Puts Scenario Status Data into the Interface Words according to the Commands which have been executed
Put Scenario Range Data into Interface Words
Status Only?
yes
no
Buffer finished?
no
yes
SIFT
Extracts the Range Data from the Interface Words
Initiate Reading of Next Buffer
RTI
1 Second?
no
yes
Average Status Data and Put on Display Stack
Error Messages?
no
yes
Put Message Codes on

2


Error Messages?
no
yes
Put Message Codes on Display Stack
Recording Data?
yes
no
CRECRD.MAC
PRECRD
Put Raw and/or Averaged Data into Buffer and Record
1/10th Second?
no
yes
RTI
POSIT.MAC
POSIT
Wrong Solution?
yes
no
Reinitialize Filter Gains and Flag Other Solution as Correct
RTI
Calculate X', Y', Z' Coordinates of RPV or Relay
VECMUL
Compute X, Y, Z Coordinates of RPV or Relay


Wrong Solution?
yes
no
Reinitialize Filter Gains and Flag Other Solution as Correct
RTI
Calculate X', Y', Z' Coordinates of RPV or Relay
VECMUL
Compute X, Y, Z Coordinates of RPV or Relay
Relateration Scenario?
no
yes
Compute X, Y, Z RPV Coordinate
Compute RPV Range
FILTER.MAC
FILTER
Smooth RPV X, Y, Z and Range Estimates
1 Second?
no
yes
WHERE
Determine Bearing, Heading, Altitude, & Speed & Put Code on Display Stack to Update Display

4

Point (FP) option (KE11-F). The EIS adds the integer multiply and divide instructions as well as two arithmetic shift instructions. The FP implements floating point addition, subtraction, multiplication, and division instructions. In order to simplify programming and to provide for a trivial transition if either only the EIS or both the EIS and the FP are obtained, all routines were coded using the standard DEC mnemonics for these instructions. These mnemonics were defined as macros in a file named FISMAC.MAC. This file was then included as one of the sources when each of the routines was assembled. The macro definitions require calls to subroutines which actually perform the calculations. These subroutines are contained in an object file named FIS40.OBJ. This file was included as one of the sources when all the routines were linked together. If the EIS and FP hardware are ever acquired, the only changes necessary to the WCCM software would be to reassemble all the files without FISMAC.MAC and to relink without FIS40.OBJ. and without OTSLIB. OBJ. The latter file is now necessary because the software floating point operations are performed using the FORTRAN-compatible routines in this file.

3.2.3. Modification Instructions

Any desired changes to any of the routines may be easily made by using the RT-11 EDIT program. The MACRO assembler is used to assemble those programs which have been modified. The general form is:

```
.R MACRO

*DK1:ONAME,DK1:LNAME=DK1:FISMAC,WCCMAC,SNAME
```

Where ONAME is the name of the object file, LNAME is the name of the list file, and SNAME is the name of the source file. FISMAC was described above. WCCMAC refers to one of the macro definition files, namely, GMACS.MAC,JMACS.MAC, and WMAC.MAC. The listing should be consulted, so that the appropriate macro definition file may be used.

The first overlay is linked as follows:

```
.R LINK

*WCCM,DK1:WCCM=DK1:COMMON,GIDIUP/C

*DK1:WDP,WD1,WD2,WD3,WD4/C

*DK1:WD5,WD6,WD7,WD8,WD9/C

*DK1:WD12,WD13,WD14,WD15,WD16/C

*DK1:DIRCOS,FIS4Ø/C

*SY:VTLIB,SYSLIB,OTSLIB
```

The second overlay link is:

```
.R LINK
*GALLOP,DK1:GALLOP=DK1:COMMON,GALLOP/C
*DK1:WDP,WD1,WD2,WD3,WD5/C
*DK1:WD7,WD10,WD11,WD12,WD13/C
*DK1:WD14,WD15,WD16/C
*DK1:COMMND,CRECRD/C
*DK1:POSIT,WHERE,FILTER,UTIL/C
*DK1:FIS4Ø/C
*SY:VTLIB,SYSLIB,OTSLIB
```

APPENDIX A

RPV LOCATION ALGORITHMS

APPENDIX A

RPV LOCATION ALGORITHMS

In this appendix we derive the algorithms developed to compute without iteration the position of an RPV for three different scenarios. These are trilateration, altitude-aided bilateration, and multilateration with a relay aircraft. The input range data are expressed in terms of the propagation delays or times-of-arrival (TOA) in the data transmission path from the master GCS to the RPV and from the RPV to the master or to another GCS. The resolution of the TOA's is $\approx$ 2.1 nanosecond which is equivalent to 0.62 meter. An accuracy of 3 meters for the RPV location is maintained through the use of a one-step linear Kalman filter which compensates for small round-off errors in the calculations and for input data which has zero-mean noise superimposed. The scenarios and the algorithms are described below.

A.1. TRILATERATION

Figure A-1 illustrates the geometry used for trilateration. The location of the RPV is determined by using the propagation delays measured between three GCS's and the RPV. These TOA's are defined as follows:

TOA1: GCS#1 to RPV to GCS#1

TOA2: GCS#1 to RPV to GCS#2

TOA3: GCS#1 to RPV to GCS#3

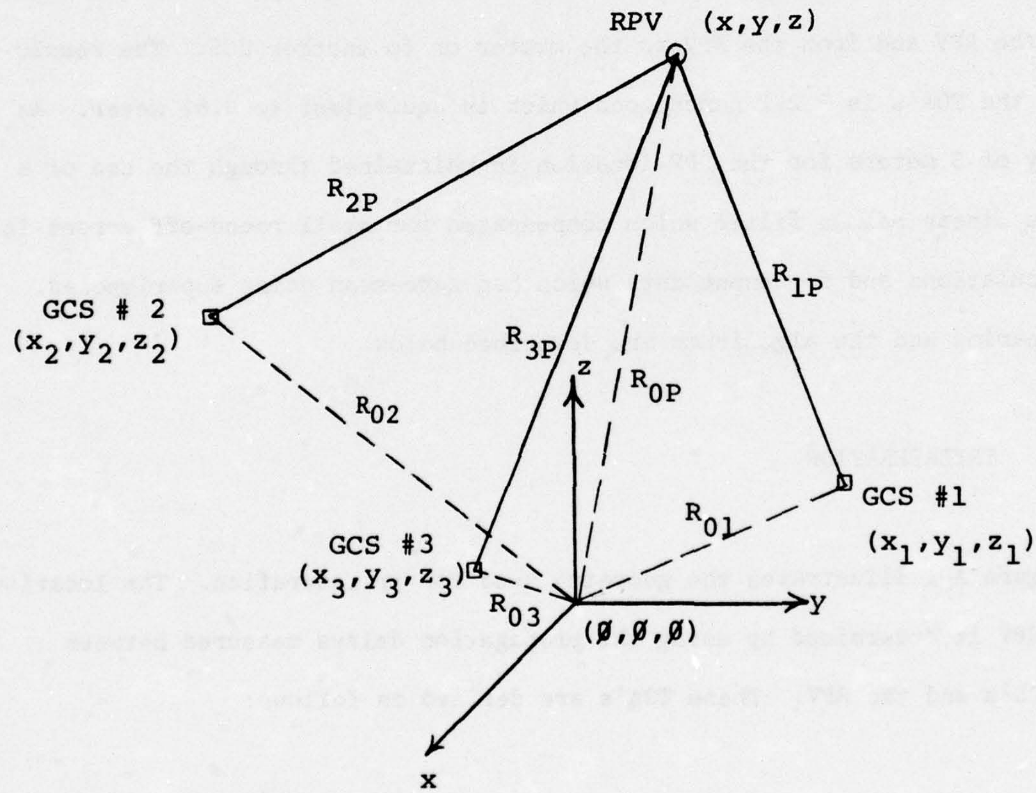


Figure A-1 Geometry of RPV Position By Trilateration

The RPV coordinates are X, Y, Z and the GCS coordinates are X_i, Y_i, Z_i where the subscript i = 1,2,3 respectively. The following slant ranges are defined:

R_{op}: origin to RPV

R_{oi}: origin to GCS (i = 1,2,3)

R_{ip}: GCS (i = 1,2,3) to RPV

With these definitions we write the following equations (see Hughes Report, p. 185):

(1) $X^2 + Y^2 + Z^2 = R_{op}^2$

(2) $X_1^2 + Y_1^2 + Z_1^2 = R_{01}^2$

(3) $X_2^2 + Y_2^2 + Z_2^2 = R_{02}^2$

(4) $X_3^2 + Y_3^2 + Z_3^2 = R_{03}^2$

(5) $(X-X_1)^2 + (Y-Y_1)^2 + (Z-Z_1)^2 = R_{1P}^2$

(6) $(X-X_2)^2 + (Y-Y_2)^2 + (Z-Z_2)^2 = R_{2P}^2$

(7) $(X-X_3)^2 + (Y-Y_3)^2 + (Z-Z_3)^2 = R_{3P}^2$

(8) $R_{1P} = \frac{1}{2}$ TOA1

(9) $R_{2P} =$ TOA2 $- \frac{1}{2}$ TOA1

(10) $R_{3P} =$ TOA3 $- \frac{1}{2}$ TOA1

The conversion from time to distance using the velocity of light (299792458 meter/second) is implicit in equations (8), (9), and (10).

In order to simplify the solution for the RPV coordinates, we transform to a primed coordinate system where the GCS coordinates are:

GCS#1: X_1, Y_1, Z_1 $\quad$ $\emptyset, \emptyset, \emptyset$

GCS#2: X_2, Y_2, Z_2 $\quad$ $X_2', \emptyset, \emptyset$

GCS#3: X_3, Y_3, Z_3 $\quad$ $X_3', Y_3', \emptyset$

In the new coordinate system equations (2) - (7) are

(11) $R_{01}^2 = \emptyset$

(12) $R_{02}^2 = (X_2')^2$

(13) $R_{03}^2 = (X_3')^2 + (Y_3')^2$

(14) $$(X')^2 + (Y')^2 + (Z')^2 = R_{1P}^2 = (\frac{1}{2}\, TOA1)^2$$

(15) $$(X' - X_2')^2 + (Y')^2 + (Z')^2 = R_{2P}^2 = (TOA2 - \frac{1}{2}\, TOA1)^2$$

(16) $$(X' - X_3')^2 \ (Y' - Y_3')^2 + (Z')^2 = R_{3P}^2 = (TOA3 - \frac{1}{2}\, TOA1)^2$$

Solving equation (15) for X' using equation (14)

(17) $$X' = \frac{1}{2} X_2' + \frac{1'}{2X_2'} (TOA2)\ (TOA1 - TOA2)$$

and solving equation (16) for Y' using equation (14)

(18) $$Y' = \frac{(X_3')^2}{2Y_3'} + \frac{Y_3'}{2} - \frac{X_3'}{Y_3'} X' + \frac{1}{2Y_3'} (TOA3)\ (TOA1 - TOA3)$$

Finally we solve equation (14) for Z'

(19) $$Z' = [(\frac{TOA1}{2})^2 - (X')^2 - (Y')^2]^{\frac{1}{2}}$$

The transformation from the primed to the original coordinate system is made using the direction cosine matrix which is derived in Section A.5.

A.2. BILATERATION

Figure A-2 illustrates the geometry used for altitude-aided bilateration. The position of the RPV is determined from the TOA's between the RPV and two ground stations and using the barometric altimeter readings which will be part

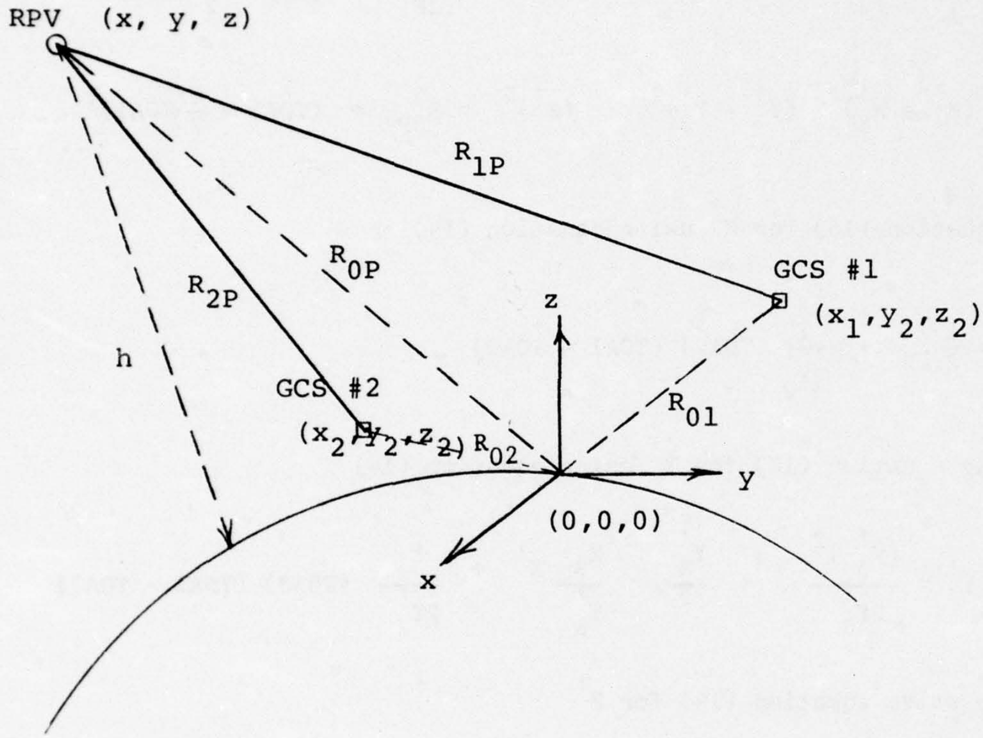


Figure A-2 Geometry Of RPV Position By Altitude-Aided Bilateration

of the telemetry data transmitted from the RPV. Defining the following variables:

h : altitude of RPV

R_E : radius of earth

and using previous definitions we write the following equations:

(21) $$X^2 + Y^2 + Z^2 = R_{0P}^2$$

(22) $$X_1^2 + Y_1^2 + Z_1^2 = R_{01}^2$$

(23) $$X_2^2 + Y_2^2 + Z_2^2 = R_{02}^2$$

(24) $$(X-X_1)^2 + (Y-Y_1)^2 + (Z-Z_1)^2 = R_{1P}^2$$

(25) $$(X-X_2)^2 + (Y-Y_2)^2 + (Z-Z_2)^2 = R_{2P}^2$$

(26) $$X^2 + Y^2 + (Z+R_E)^2 = (R_E+h)^2$$

(27) $$R_{1P} = \frac{1}{2}\,\text{TOA1}$$

(28) $$R_{2P} = \text{TOA2} - \frac{1}{2}\,\text{TOA1}$$

Equation (26) is derived in section A.3. Comparing this equation and equation (7), we see that they are identical if we equate $X_3=0$, $Y_3=0$, $Z_3=-R_E$, $R_{3P}=R_E+h$. Thus, using the altitude in the bilateration scenario is equivalent to having the third GCS at the center of the earth in the trilateration scenario.

We again use the coordinate transformation described previously.

GCS#1:	X_1, Y_1, Z_1	$\emptyset, \emptyset, \emptyset$
GCS#2:	X_2, Y_2, Z_2	$X_2', \emptyset, \emptyset$
altitude:	$\emptyset, \emptyset, -R_E$	$X_3', Y_3', \emptyset$

Rewriting equations (24) - (26)

$$(27) \quad (X')^2 + (Y')^2 + (Z')^2 = \left(\frac{TOA1}{2}\right)^2$$

$$(28) \quad (X'-X_2')^2 + (Y')^2 + (Z')^2 = \left(TOA2 - \frac{1}{2}\,TOA1\right)^2$$

$$(29) \quad (X'-X_3')^2 + (Y'-Y_3') + (Z')^2 = (R_E+h)^2$$

Solving as before for X', Y', and Z' we obtain

$$(30) \quad X' = \frac{X_2'}{2} + \frac{1}{2X_2'}\,(TOA2)\,(TOA1-TOA2)$$

$$(31)\quad Y' = \frac{(X_3')^2}{2Y_3'} + \frac{Y_3'}{2} - \frac{X_3'}{Y_3'}X' + \frac{1}{2Y_3'}\left[\left(\frac{TOA1}{2}\right)^2 - (R_E+h)^2\right]$$

$$(32)\quad Z' = \left[\left(\frac{TOA1}{2}\right)^2 - (X')^2 - (Y')^2\right]^{\frac{1}{2}}$$

In this case the direction cosine matrix is also used to transform back to the original coordinate system.

A.3. CORRECTIONS DUE TO CURVATURE OF EARTH'S SURFACE

Equation (26) is due to the fact that the Z-coordinate of the RPV is not identically the RPV altitude, but must be corrected for the curvature of the earth. Consider Figure A-3 where the problem is shown two dimensionally. The axis, S, lies in the x-y plane which is tangent to the earth's surface. The variables are h, the altitude of the RPV, R, the slant range from the origin to the RPV, R_E, the radius of the Earth, and ε, the angle at the center of the Earth between the origin and the RPV. In terms of these variables the RPV coordinates are

$$(30)\quad S = (R_E+h)\sin\varepsilon$$

$$(31)\quad Z = (R_E+h)\cos\varepsilon - R_E$$

Using the trigonometric law of cosines

$$(32)\quad R^2 = R_E^{\,2} + (R_E+h)^2 - 2R_E(R_E+h)\cos\varepsilon$$

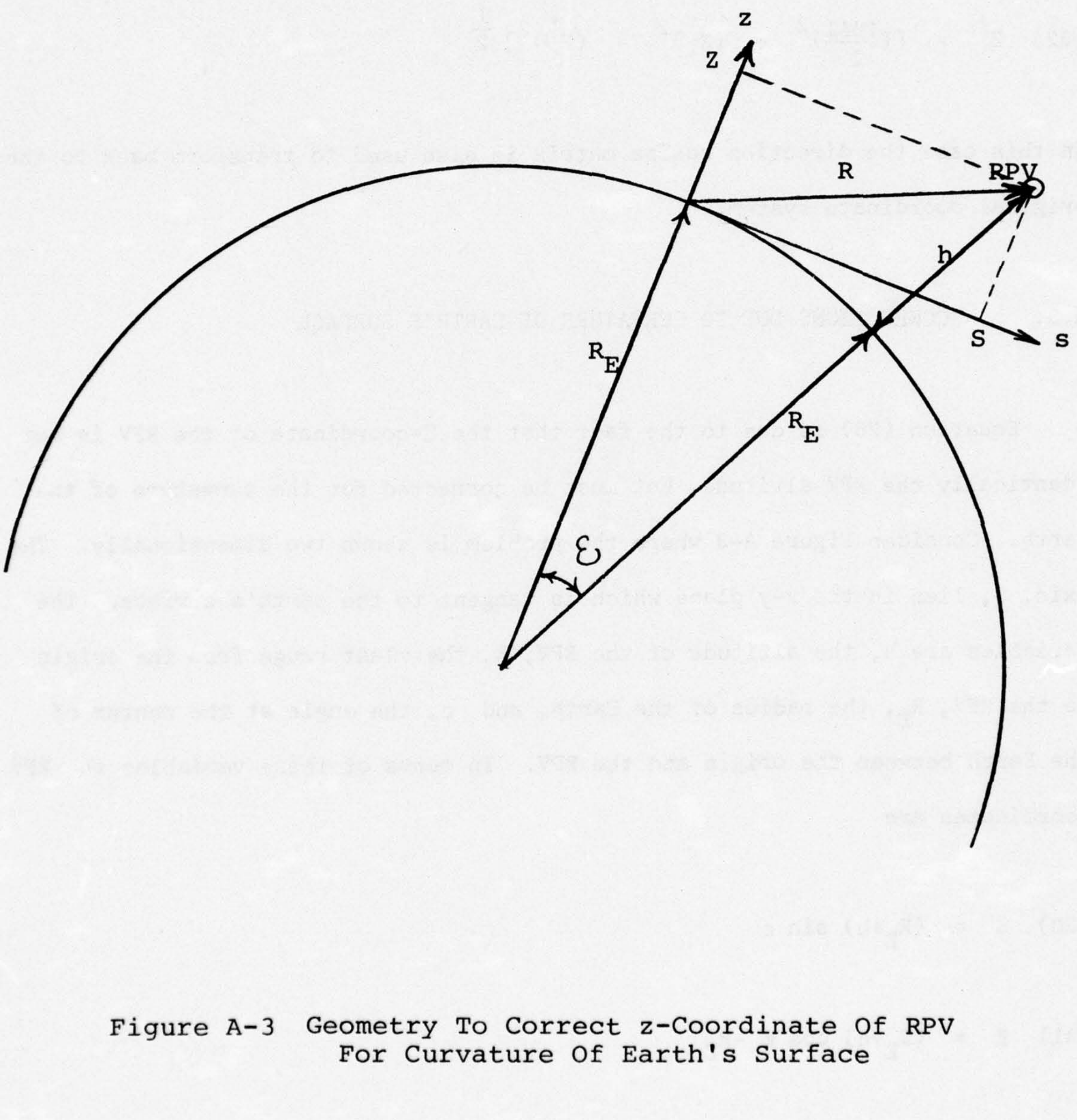


Figure A-3 Geometry To Correct z-Coordinate Of RPV
For Curvature Of Earth's Surface

Solving for $\cos \varepsilon$

$$(33) \quad \cos \varepsilon = \frac{1}{R_E + h} \left[R_E + h\left(1 + \frac{h}{2R_E}\right) - \frac{R^2}{2R_E} \right]$$

Using (33) in (31)

$$(34) \quad Z = h\left(1 + \frac{h}{2R_E}\right) - \frac{R^2}{2R_E}$$

Generalizing to three dimensions, remembering that $R^2 = X^2 + Y^2 + Z^2$, we have equation (26)

$$(26) \quad X^2 + Y^2 + (Z + R_E)^2 = (R_E + h)^2$$

A.4. CORRECTION DUE TO NON-SPHERICITY OF THE EARTH

In order to maintain the accuracy of the RPV location calculations, the value used for the radius of the earth was found using the fact that the shape of the earth is not spherical, but ellipsoidal. Figure A-4 shows the earth in an exaggerated cross sectional view. E and P are respectively the equatorial radius (6378.388 km) and polar radius (6356.912 km). λ is the latitude.

Remembering the equation of an ellipse

$$(36) \quad \frac{S^2}{E^2} + \frac{Z^2}{P^2} = 1$$

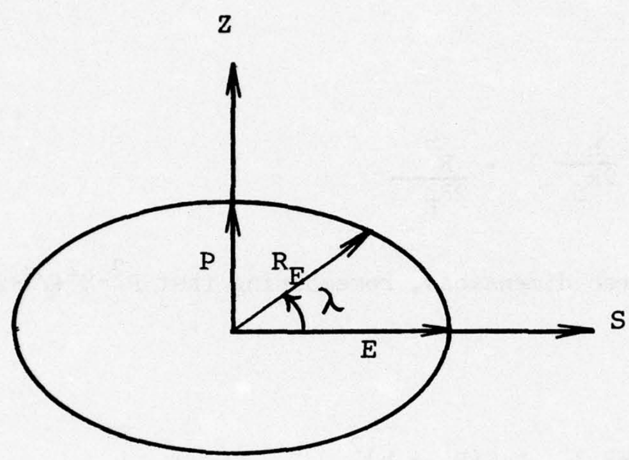


Figure A-4 Geometry For Finding The Radius Of The Earth At Any Latitude

and the transformations

$$S = R_E \cos\lambda \ , \ \ Z = R_E \sin\lambda$$

we have

$$(35) \quad R_E^2\,(P^2\cos^2\lambda + E^2\sin^2\lambda) = P^2E^2$$

We have set $\lambda = 45°$ since RADC is located at very nearly this latitude. Equation (35) reduces to

$$(36) \quad R_E(\lambda{=}45°) = PE\left[\tfrac{1}{2}(P^2+E^2)\right]^{-\frac{1}{2}} = 6367.623 \text{ km.}$$

A.5. DIRECTION COSINE MATRIX

We now derive the direction cosine matrix which is used to transform from the primed to the original coordinate system. Recall that the coordinates of the GCS's were as follows:

GCS#1: $X_1, Y_1, Z_1, \rightarrow \emptyset, \emptyset, \emptyset$

GCS#2: $X_2, Y_2, Z_2 \rightarrow X_2', \emptyset, \emptyset$

GCS#3: $X_3, Y_3, Z_3 \rightarrow X_3', Y_3', \emptyset$

This is accomplished by a translation and three rotations, namely:

Step 1: Translate origin to GCS#1

$$X_1^T, Y_1^T, Z_1^T = \emptyset,\emptyset,\emptyset$$

Step 2: Rotate about Z^T axis to give $Y_2^S=\emptyset$

$$X_2^S, Y_2^S, Z_2^S = X_2^S, \emptyset, Z_2^S$$

Step 3: Rotate about Y^S axis to give $Z_2^R=\emptyset$

$$X_2^R, Y_2^R, Z_2^R = X_2^R, \emptyset, \emptyset$$

Step 4: Rotate about X^R axis to give $Z_3'=\emptyset$

$$X_3', Y_3', Z_3' = X_3', Y_3', \emptyset$$

Figure A-5 shows a rotational coordinate transformation in two dimensions. The general transformation equations are

(38) $u' = u \cos\theta + v \sin\theta$

(39) $v' = -u \sin\theta + v \cos\theta$

Steps 2, 3, 4 show that the desired rotation is to put a known point, u_P, v_P, on the u' axis. Equations (38) and (39) then show

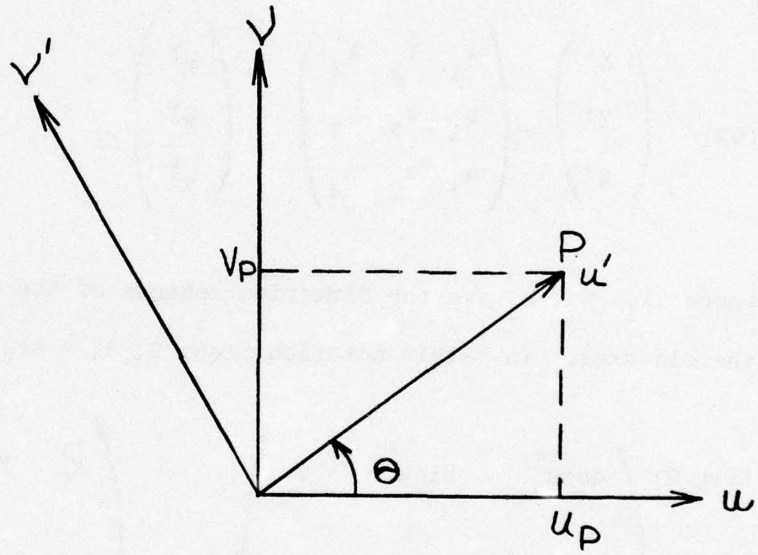


Figure A-5 Rotation Of Coordinates In Two Dimensions

$$\sin\theta = v_P\,(u_P^2 + v_P^2)^{-\frac{1}{2}} \tag{40}$$

$$\cos\theta = u_P(u_P^2 + v_P^2)^{-\frac{1}{2}} \tag{41}$$

The rotation transformation in three dimensions is conveniently expressed in matrix form:

$$\begin{pmatrix} X' \\ Y' \\ Z' \end{pmatrix} = \begin{pmatrix} \lambda_1 & \lambda_2 & \lambda_3 \\ \mu_1 & \mu_2 & \mu_3 \\ \alpha_1 & \alpha_2 & \alpha_3 \end{pmatrix} \begin{pmatrix} X^T \\ Y^T \\ Z^T \end{pmatrix} \tag{42}$$

where λ_i, μ_i, α_i are the direction cosines of the new axes with respect to the old axes. In matrix notation Steps 2, 3, 4 are:

Step 2:

$$\begin{pmatrix} \cos\theta_2^T & \mathrm{Sin}\theta_2^T & \emptyset \\ -\sin\theta_2^T & \cos\theta_2^T & \emptyset \\ \emptyset & \emptyset & 1 \end{pmatrix} = \frac{1}{R} \begin{pmatrix} X_2^T & Y_2^T & \emptyset \\ -Y_2^T & X_2^T & \emptyset \\ \emptyset & \emptyset & R \end{pmatrix} \tag{43}$$

Step 3:

$$\begin{pmatrix} \cos\theta_2^S & \emptyset & \sin\theta_2^S \\ \emptyset & 1 & \emptyset \\ -\sin\theta_2^S & \emptyset & \cos\theta_2^S \end{pmatrix} = \frac{1}{Q} \begin{pmatrix} X_2^S & \emptyset & Z_2^S \\ \emptyset & Q & \emptyset \\ -Z_2^S & \emptyset & X_2^S \end{pmatrix} \tag{44}$$

Step 4:

$$(45)\quad \begin{pmatrix} 1 & \emptyset & \emptyset \\ \emptyset & \cos\theta_3^R & \sin\theta_3^R \\ \emptyset & -\sin\theta_3^R & \cos\theta_R^3 \end{pmatrix} = \frac{1}{P} \begin{pmatrix} P & \emptyset & \emptyset \\ \emptyset & Y_3^R & Z_3^R \\ \emptyset & -Z_3^R & Y_3^R \end{pmatrix}$$

where

$$(46)\qquad R = [(X_2^T)^2 + (Y_2^T)^2]^{\frac{1}{2}}$$

$$(47)\qquad Q = [(X_2^S)^2 + (Z_2^S)^2]^{\frac{1}{2}}$$

$$(48)\qquad P = [(Y_3^R)^2 + (Z_3^R)^2]^{\frac{1}{2}}$$

In what follows we express the results in terms of the translated coordinates

$$(49)\quad X_2^T = X_{21} = X_2 - X_1 \qquad (52)\quad X_3^T = X_{31} = X_3 - X_1$$

$$(50)\quad Y_2^T = Y_{21} = Y_2 - Y_1 \qquad (53)\quad Y_3^T = Y_{31} = Y_3 - Y_1$$

$$(51)\quad Z_2^T = Z_{21} = Z_2 - Z_1 \qquad (54)\quad Z_3^T = Z_{31} = Z_3 - Z_1$$

Step 2:

$$(55)\quad \begin{pmatrix} X_2^S \\ Y_2^S \\ Z_2^S \end{pmatrix} = \frac{1}{R} \begin{pmatrix} X_{21} & Y_{21} & \emptyset \\ -Y_{21} & X_{21} & \emptyset \\ \emptyset & \emptyset & R \end{pmatrix} \begin{pmatrix} X_{21} \\ Y_{21} \\ Z_{21} \end{pmatrix} = \begin{pmatrix} R \\ \emptyset \\ Z_{21} \end{pmatrix}$$

$$(56)\quad \begin{pmatrix} X_3^S \\ Y_3^S \\ Z_3^S \end{pmatrix} = \frac{1}{R} \begin{pmatrix} X_{21} & Y_{21} & \emptyset \\ -Y_{21} & X_{21} & \emptyset \\ \emptyset & \emptyset & R \end{pmatrix} \begin{pmatrix} X_{31} \\ Y_{31} \\ Z_{31} \end{pmatrix} = \begin{pmatrix} A/R \\ B/R \\ Z_{31} \end{pmatrix}$$

where

$$(57)\quad R = (X_{21}^2 + Y_{21}^2)^{\frac{1}{2}}$$

$$(58)\quad A = X_{21}X_{31} + Y_{21}Y_{31}$$

$$(59)\quad B = Y_{21}X_{31} + X_{21}Y_{31}$$

Step 3:

$$(60)\quad \begin{pmatrix} X_2^R \\ Y_2^R \\ Z_2^R \end{pmatrix} = \frac{1}{Q} \begin{pmatrix} R & \emptyset & Z_{21} \\ \emptyset & Q & \emptyset \\ -Z_{21} & \emptyset & R \end{pmatrix} \begin{pmatrix} R \\ \emptyset \\ Z_{21} \end{pmatrix} = \begin{pmatrix} Q \\ \emptyset \\ \emptyset \end{pmatrix}$$

$$(61)\quad \begin{pmatrix} X_3^R \\ Y_3^R \\ Z_3^R \end{pmatrix} = \frac{1}{Q} \begin{pmatrix} R & \emptyset & Z_{21} \\ \emptyset & Q & \emptyset \\ -Z_{21} & \emptyset & R \end{pmatrix} \begin{pmatrix} A/R \\ B/R \\ Z_{31} \end{pmatrix} = \begin{pmatrix} C/Q \\ B/R \\ D/RQ \end{pmatrix}$$

where

$$(62)\quad Q = (X_{21}^2 + Y_{21}^2 + Z_{21}^2)^{\frac{1}{2}}$$

$$(63)\quad C = X_{21}X_{31} + Y_{21}Y_{31} + Z_{21}Z_{31}$$

$$(64)\quad D = -(X_{21}X_{31} + Y_{21}Y_{31})\, Z_{21} + R^2\, Z_{31}$$

Step 4:

$$(65)\quad \begin{pmatrix} X_2' \\ Y_2' \\ Z_2' \end{pmatrix} = \frac{1}{P} \begin{pmatrix} P & \emptyset & \emptyset \\ \emptyset & B/R & D/RQ \\ \emptyset & -D/RQ & B/R \end{pmatrix} \begin{pmatrix} Q \\ \emptyset \\ \emptyset \end{pmatrix} = \begin{pmatrix} Q \\ \emptyset \\ \emptyset \end{pmatrix}$$

$$(66)\quad \begin{pmatrix} X_3' \\ Y_3' \\ Z_3' \end{pmatrix} = \frac{1}{P} \begin{pmatrix} P & \emptyset & \emptyset \\ \emptyset & B/R & D/RQ \\ \emptyset & -D/RQ & B/R \end{pmatrix} \begin{pmatrix} C/Q \\ B/R \\ D/RQ \end{pmatrix} = \begin{pmatrix} C/Q \\ P \\ \emptyset \end{pmatrix}$$

where

$$(67) \qquad P = [(B/R)^2 + (D/RQ)^2]^{\frac{1}{2}}$$

The values given by equations (65) and (66) are used in equations (17), (18), (19) for the trilateration scenario and equations (30), (31), (32) for the bilateration scenario. The matrix needed to transform from the original X, Y, Z coordinate system to the primed X', Y', Z' coordinate system is obtained by multiplying the three individual rotation matrices, i.e.,

$$(68) \quad \underline{D} = \begin{pmatrix} \lambda_1 & \lambda_2 & \lambda_3 \\ \mu_1 & \mu_2 & \mu_3 \\ \alpha_1 & \alpha_2 & \alpha_3 \end{pmatrix} = \frac{1}{P} \begin{pmatrix} P & 0 & 0 \\ 0 & B/R & D/RQ \\ 0 & -D/RQ & B/R \end{pmatrix} \frac{1}{Q} \begin{pmatrix} R & 0 & Z_{21} \\ 0 & Q & 0 \\ -Z_{21} & 0 & R \end{pmatrix} \frac{1}{R} \begin{pmatrix} X_{21} & Y_{21} & 0 \\ -Y_{21} & X_{21} & 0 \\ 0 & 0 & R \end{pmatrix}$$

$$= \begin{pmatrix} \dfrac{X_{21}}{Q} & \dfrac{Y_{21}}{Q} & \dfrac{Z_{21}}{Q} \\[2ex] \dfrac{X_{31}E_1 - X_{21}F_1}{G\ Q} & \dfrac{X_{31}G_2 - X_{21}F_2}{G\ Q} & \dfrac{Z_{31}F_3 - Z_{21}F_3}{G\ Q} \\[2ex] G_1/G & G_2/G & G_3/G \end{pmatrix}$$

where

$$(69) \qquad E_1 = Y_{21}^2 + Z_{21}^2$$

$$(70) \qquad E_2 = X_{21}^2 + Z_{21}^2$$

(71) $$E_3 = X_{21}^2 + Y_{21}^2$$

(72) $$F_1 = Y_{21}Y_{31} + Z_{21}Z_{31}$$

(73) $$F_2 = X_{21}X_{31} + Z_{21}Z_{31}$$

(74) $$F_3 = X_{21}X_{31} + Y_{21}Y_{31}$$

(75) $$G_1 = Y_{21}Z_{31} - Y_{31}Z_{21}$$

(76) $$G_2 = X_{31}Z_{21} - X_{21}Z_{31}$$

(77) $$G_3 = X_{21}Y_{31} - X_{31}Y_{21}$$

(78) $$G = (A_1^2 + A_2^2 + A_3^2)^{\frac{1}{2}}$$

The transformation from the primed to the original coordinate system is made using the transpose of the direction cosine matrix

(79) $$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} \lambda_1 & \mu_1 & \alpha_1 \\ \lambda_2 & \mu_2 & \alpha_2 \\ \lambda_3 & \mu_3 & \alpha_3 \end{pmatrix} \begin{pmatrix} X' \\ Y' \\ Z' \end{pmatrix} + \begin{pmatrix} X_1 \\ Y_1 \\ Z_1 \end{pmatrix}$$

A.6 Relateration

Figure A-6 illustrates the geometry used in the determination of the RPV position by multilateration using a relay aircraft. In this scenario, the relay vehicle and one GCS (i.e., #3) have a direct line of sight to the RPV. The other GCS's communicate with the RPV through the relay. The position of the relay is found by trilateration as previously described. The RPV location is determined by bilateration with the relay and GCS#3 plus the RPV altitude. The computations are complicated by the motion of the relay which results in a constantly changing direction cosine matrix. It was not considered practical to continually recalculate the RPV direction cosine matrix because too much time would be taken and too much core space would be used. Therefore, a bilateration algorithm was developed which required only a translation of coordinates.

We define five propagation delays:

TOA1:	GCS#1 to relay to GCS#1
TOA2:	GCS#1 to relay to GCS#2
TOA3:	GCS#1 to relay to GCS#3
TOA4:	GCS#1 to relay to RPV to relay to GCS#1
TOA5:	GCS#1 to relay to RPV to GCS#3

and the relay aircraft coordinates, X_R, Y_R, Z_R. The range from the relay to the RPV is R_{RP}. The position of the RPV is computed using the following equations:

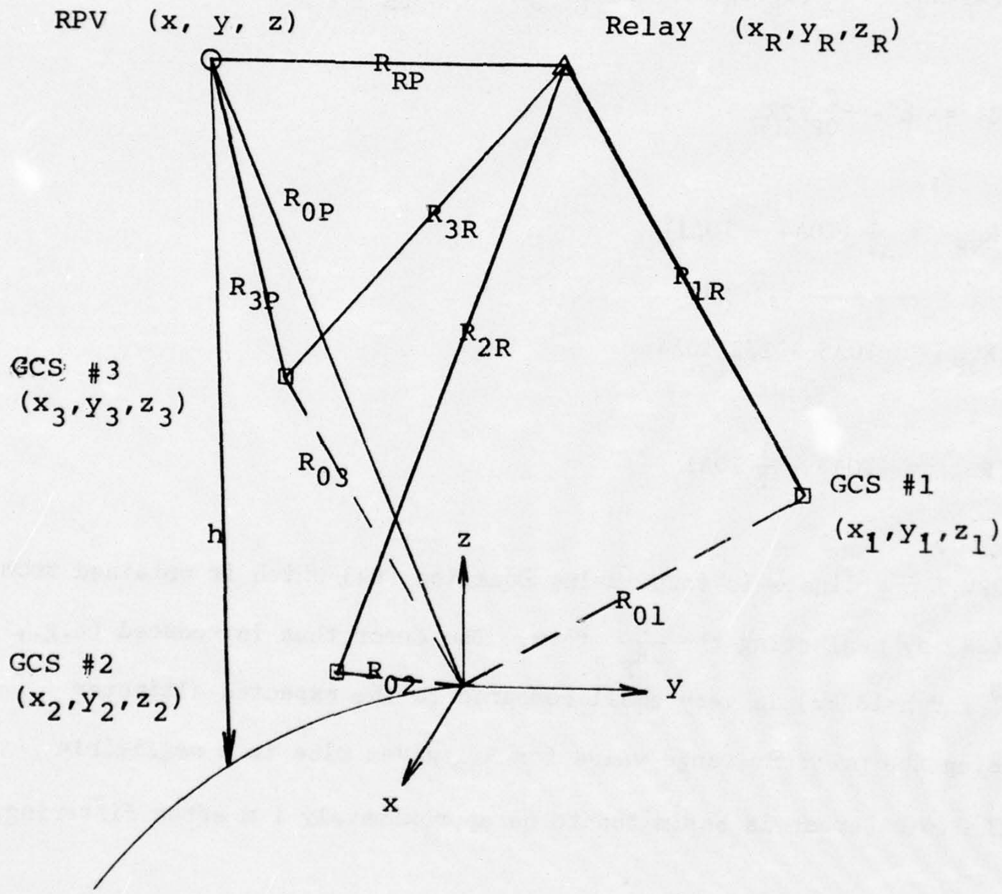


Figure A-6 Geometry of RPV Position By Multilateration With Relay Aircraft

(81) $$(X-X_R)^2 + (Y-Y_R)^2 + (Z-Z_R)^2 = R_{RP}^2$$

(82) $$(X-X_3)^2 + (Y-Y_3)^2 + (Z-Z_3)^2 = R_{3P}^2$$

(83) $$(X_R-X_3)^2 + (Y_R-Y_3)^2 + (Z_R-Z_3)^2 = R_{3R}^2$$

(84) $$Z = h - R_{0P}^2/2R_E$$

(85) $$R_{RP} = \frac{1}{2}(TOA4 - TOA1)$$

(86) $$R_{3P} = TOA5 - 1/2\ TOA4$$

(87) $$R_{3R} = TOA3 - \frac{1}{2}TOA1$$

The RPV Z coordinate is found using Equation (84) which is obtained from equation (34) by neglecting the $\frac{h}{2R_E}$ term. The error thus introduced (e.g., $\frac{h}{2R_E} = 10^{-3}$ for h=13 km) is very small compared to the expected altimeter error. Using the previous range value for R_{0P} gives rise to a negligible error. The total error is estimated to be approximately 1 m after filtering.

The origin of the coordinate system is translated to GCS#3 so that

$$X' = X-X_3, \quad Y' = Y-Y_3, \quad Z' = Z-Z_3$$

$$X_R' = X_R-X_3, \quad Y_R' = Y_R-Y_3, \quad Z_R' = Z_R-Z_3$$

Then equation (82) is

$$(88)\ (X')^2 + (Y')^2 + (Z')^2 = R_{3P}^2 = (TOA5 - 1/2\ TOA4)^2 = V$$

and equation (81) is

$$(89)\ (X'-X_R')^2 + (Y'-y_R')^2 + (Z'-Z_R')^2 = R_{RP}^2$$

which becomes

$$(90)\ X'X'_R + Y'Y_R' + Z'Z_R' = \frac{1}{2}\,[(TOA5 - 1/2\ TOA4)^2 \quad (TOA3 - \frac{1}{2}TOA1)^2$$

$$- 1/4(TOA4 - TOA1)^2]$$

where we have used equations (82), (83), (85), (86), and (87). Rewrite equation (88) as

$$(91)\ (X')^2 + (Y')^2 = (TOA5 - 1/2\ TOA4)^2 - (Z')^2$$

and equation (90) as

$$(92)\ X' = \frac{1}{X_R'}\,[U - Y'Y_R']$$

where

$$U = \frac{1}{2}\,[(TOA5 - \frac{1}{2}\,TOA4)^2 + (TOA3 - \frac{1}{2}\,TOA1)^2 - \frac{1}{4}\,(TOA4 - TOA1)^2] - Z'Z_R'$$

Substituting (92) into (91) and solving for Y' we have

$$(93)\quad Y' = A \pm (B + C)^{\frac{1}{2}}$$

where

$$A = \frac{U\, Y_R'}{(X_R')^2 + (Y_R')^2}$$

$$B = -\left[\frac{U}{(X_R')^2 + (Y_R')^2}\right]^2$$

$$C = \frac{(TOA5 - 1/2\ TOA4)^2 - (Z')^2}{(X_R')^2 + (Y_R')^2}$$

The number obtained for Y' is used in equation (91) to give X'. The X and Y values for the RPV are found by translating back to the original coordinate system.

A.7 Kalman Filter

A linear Kalman Filter is used to smooth the RPV X, Y, Z, and range estimates which are calculated for the three different scenarios described above. The filtering is necessary to improve the accuracy of the location process so that the effects of the TOA resolution, noise, geometry and computational round-off are minimized. The basic iterative form of the Kalman filter is

$$(95) \qquad \gamma_{k+1} = \gamma_k + V_k \Delta t + \frac{P_k + \tau_u{}^2}{P_k + \tau^2} [y_{k+1} - (\gamma_k + V_k \Delta t)]$$

where

γ_k	refers to the previous filtered estimate of X, Y, Z, or R
y_{k+1}	refers to the present calculated estimate of X,Y,Z, or R
V_k	is the velocity component
Δ_t	is the time interval
σ_u	is the velocity component uncertainty
σ_n	is the parameter estimate uncertainty
$\sigma^2 = \sigma_u^2 + \sigma_n^2$	
P_k	is the uncertainty in the filtered parameter

Noting that

$$(96) \qquad V_k \Delta t = \gamma_k - \gamma_{k-1}$$

and defining (97) $S_k = 2\,\gamma_k - \gamma_{k-1}$ and the Kalman filter gain as

$$(98) \qquad C_k = \frac{P_k + \sigma_u^2}{P_k + \sigma^2}$$

and equation (95) becomes

$$(99) \qquad \gamma_{k+1} = S_k + C_k [y_{k+1} - S_k]$$

The Kalman gain is updated at every pass and the updated uncertainty is defined as

$$(100) \qquad P_{k+1} = \frac{\tau_n^2 P_k + \tau_u^2}{P_k + \tau^2}$$

Therefore

$$(101) \qquad C_{k+1} = \frac{P_{k+1} + \sigma_u^2}{P_{k+1} + \sigma^2} = \frac{C_k \sigma_n^2 + \sigma_u^2}{C_k \sigma_n^2 + \sigma^2}$$

On the initial pass V_K is set to zero and calculated values are used for the Y_k.

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